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ARTICLE

Hydrological Assessment of the "Madar 22" Weather Event: Implications for Water Resources Management in Saudi Arabia

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ABSTRACT

A rare and intense tropical weather event, named "Madar 22" affected large areas of the Kingdom of Saudi Arabia and neighboring Gulf countries during July and August 2022. This study aims to assess the hydrological impacts of the event on both surface and groundwater resources, and its implications for water resources management in the Kingdom. Also, one of the specific objectives of the present study is to estimate both runoff and potential groundwater recharge coefficients during "Madar 22" weather event across all regions of Saudi Arabia. Utilizing rainfall data from the MEWA hydrological network and ArcGIS-based spatial analysis, the event was found to deliver extreme precipitation equivalent to a 10-year return period for a 3-hour storm. The event generated a total rainfall volume of 20.6 billion cubic meters, of which 1.058 billion cubic meters was estimated as surface runoff. This led to the harvesting of 294 million cubic meters in 189 dam reservoirs and recharged an estimated 239 million cubic meters of groundwater, as indicated by water table rises in 65 shallow wells. The present study concluded that the mean precipitation depth recorded in August 2022 is substantially higher than the long-term monthly average, illustrating a clear trend toward intensified late-summer rainfall. The findings of the present study show critical implications for renewable water resource management in arid and semi-arid regions.

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They emphasize the need to integrate extreme weather events into flood risk assessments, dam operation protocols, and groundwater recharge strategies to enhance national climate resilience.

Keywords: Extreme Weather; Groundwater Recharge; Flood Risk, Dam Storage; Saudi Arabia

1. Introduction

The Arab region comprises 14 of the world's 20 most water-stressed countries. Its annual internal water resources account for only 6% of its average annual precipitation, in stark contrast to the global average of 38% [1]. The scarcity of renewable water resources represents a critical challenge for the Arabian Gulf countries, all of which are located in arid and extremely arid climatic zones [2]. The Kingdom of Saudi Arabia lies in one of the most arid regions globally, characterized by a dry climate, elevated temperatures, and low precipitation levels across most parts of the country. The average annual precipitation is estimated at 103 mm/year, ranging from approximately 20 mm in the southeastern Empty Quarter to about 550 mm in the highlands of the southwestern regions [3]. Consequently, the surface runoff generated during the limited rainy seasons is considered a vital renewable water resource essential for meeting growing water demand, supporting economic development, and sustaining rapid urban population growth. In Saudi Arabia, heavy rainstorms occur infrequently, typically on only a few days each year, and display strong spatial variability and a sporadic distribution pattern across different regions. The annual rainfall and temperature data across Saudi Arabia from 1978 to 2009 have showed notable and accelerated decline in rainfall during the more recent period (1994–2009) compared to the full analysis period (1978–2009) [4]. The intensity–duration–frequency (IDF) curves for the Kingdom of Saudi Arabia have been developed based on the analyses of rainfall data collected from 28 meteorological stations with 20 to 28 years of records, with storm durations ranging from 10 minutes to 24 hours [5]. Rainfall trends and extremes in Saudi Arabia between 1978 and 2019 were examined and an overall decline in annual precipitation across the country was observed [6]. However, this long-term decreasing trend was contrasted by an increase in rainfall totals during the most recent decade, indicating a possible shift in climatic patterns. These changes suggest a growing trend toward rainfall extremes rather than gradual or moderate precipitation. Spatially, the occurrence of extreme rainfall was found to be more frequent in the northwest, eastern, and southwestern regions of the Kingdom, highlighting specific areas of heightened flood risk due to changing precipitation dynamics [6]. Mountainous, urbanized, and arid regions such as Saudi Arabia are particularly vulnerable to flooding caused by sudden and intense rainstorms, which can significantly impact human settlements, infrastructure, and the ecological and biophysical environment [7]. The adopted remote sensing and GIS techniques are reliable and cost-effective and could potentially be applied to identify potential risk locations to protect local settlers, support planners, and improve disaster response services during intense rainfall conditions [8]. Approximately 30 distinctive weather events have occurred in the Kingdom of Saudi Arabia during different climatic seasons [9]. Among these events, "Al Baydaa" event took place from 25 April to 8 May 2013; "Al Rabab" event extended from 28 July to 3 August 2016; "Joud" occurred from 11 to 18 April 2017; and "Ghadaq" event lasted from 25 October to 20 November 2018. Beginning around 2030, interannual precipitation variability in Saudi Arabia is projected to increase by up to 60%. This heightened variability is expected to result in a higher frequency of both drought and flood events, placing additional stress on water resource management systems [10]. Rainfall is a critical component of the hydrological cycle, affecting ecosystems, agriculture, and urban infrastructure. While sporadic rain can be absorbed by soil and utilized by vegetation, prolonged rainfall poses challenges to natural and built environments. One of the primary hydrological consequences of extended precipitation is the saturation of the soil profile, which subsequently leads to increased surface runoff. Understanding this process is essential for managing flood risks, designing effective drainage systems, and preserving soil health. The impacts of rainfall and soil moisture on the flood hazards in a humid mountainous area were investigated by Yu et al., who concluded the relative importance of rainfall and antecedent soil moisture on flood generation [11], where there is a correlation between the ratio of antecedent soil saturation ratio to rainfall and peak flow.

In the summer of 2020, the western and southwestern regions of Saudi Arabia, along with parts of neighboring countries such as Oman, the United Arab Emirates, and Yemen, experienced a distinctive summer weather event called "Rahw," which lasted 18 days, from 24 July to 10 August 2020. Jeddah, located in the Makkah region, was affected by several severe thunderstorm events. The most recent occurred on 24 November 2022, during which a substantial amount of precipitation reaching 182 mm was recorded within just six hours. The relationship between dam operational plans and downstream drought occurrences, aiming to optimize dam operations for drought mitigation in southwestern Saudi Arabia was studied by Hakami et al. who provided insights into the interaction between dam management practices and hydroclimatic factors [12]. Saudi Arabia has experienced numerous heavy to moderate rainstorms in the past, including 17.4 mm of rainfall on 12 August 1977 in Riyadh; 11 mm on 14 August 1992 in Tabuk; 19.4 mm on 26 August 1993 in Al-Ahsa in the Eastern Region; and 9 mm on 28 August 1994 in the Al Jouf region. More recently, on 23 July 2022, large geographical areas of Saudi Arabia as well as neighboring countries in the Arabian Gulf, including Oman, the United Arab Emirates, Qatar, Bahrain, and Iran were affected by a rare and distinctive tropical summer weather event. This event was notable for its spatial extent and intensity, resulting in widespread flooding across Saudi Arabia and several Arabian Gulf countries. The Committee for the Naming of Distinctive Weather Events in the Kingdom of Saudi Arabia officially named the event "Madar 22." The name "Madar" is derived from the Arabic word meaning "tropic," and "22" refers to the year 2022. Meteorologists attributed the origin of the "Madar 22" event to a tropical depression, which developed due to unusual seasonal wind activity over the Indian Ocean and the Arabian Sea.

2. Aim of the Study

Few studies have been published assessing the hydrological impacts of extreme summer weather events in the Kingdom of Saudi Arabia or other Gulf Cooperation Council (GCC) countries. Among the limited literature, the study by Mattar and Al Ghamdi investigated the hydrometeorological impacts of the notable summer weather event known as "Rahw," which affected the southwestern regions of the Kingdom in July and August 2020 [9]. During this event, regions including Al Madinah, Makkah, Al Baha, Asir, Jazan, and Najran experienced moderate to heavy daily rainfall similar in both timing and geographical distribution to the "Madar 22" weather event. Accordingly, the present study aims to achieve the following objectives:

- Evaluate the hydrological implications of "Madar 22" event for water resources management in the Kingdom of Saudi Arabia.
- Analyze the spatial and temporal rainfall patterns during "Madar 22" weather event.
- Investigate the correlation between estimated rainfall and resulting runoff depths and volumes, including those collected in dam reservoirs during the event.
- Estimate both runoff and potential groundwater recharge coefficients during "Madar 22" weather event across all regions of Saudi Arabia.
- Assess the hydrological impacts of "Madar 22" weather event on both surface and groundwater resources in the Kingdom.
- Update Dam Operation and Maintenance Protocols during extreme events in Saudi Arabia.

3. Methodology and Data Collection

Daily and hourly records from the hydrologic network stations of the Ministry of Environment, Water, and Agriculture (MEWA), comprising 360 rain and weather stations (**Table 1**), were obtained for analysis. The data can be accessed through the General Directorate for Water Resources in the Ministry of Environment, Water and Agriculture (MEWA). These records were used to perform spatial distribution analyses of rainfall and groundwater levels in shallow aquifers and to generate regional geographic maps during "Madar 22" event. Statistical and spatial analyses were conducted using Arc GIS techniques. The maximum daily precipitation for each region during the "Madar 22" event was calculated, and the weighted precipitation across all regions of Saudi Arabia was determined using ArcGIS spatial interpolation methods. Furthermore, daily, and monthly precipitation data from these stations were correlated with corresponding historical records over a 40-year period. The results of the spatial distribution analysis for "Madar 22" were compared with those of the summer weather event

"Rahw," which affected southwestern Saudi Arabia from 24 July to 10 August 2020. In addition, daily records from 189 dam reservoirs and 160 groundwater monitoring wells were analyzed to estimate both the volume of harvested runoff and the rise in groundwater levels during the "Madar 22" event. The locations of MEWA hydrologic network stations that recorded rainfall during the "Madar 22" event are illustrated in **Figure 1**.

Table 1. Numbers of Rainfall and Weather Stations Have Recorded Rainfall During "Madar 22" Weather Event.

Region	Number of Weather and Rainfall Stations in MEWA Hydrologic Network	Number of Hydrologic Networks Recorded Rainfall During Madar 2022
Riyadh	78	51
Makkah	108	77
Al Madinah	80	45
Eastern Region	34	19
Asir	83	48
Najran	6	6
Jazan	41	26
Al-Jouf	14	8
Northern Borders	12	6
Al Qassim	34	19
Tabuk	36	29
Al Bahah	22	14
Hail	25	12
Total	573	360

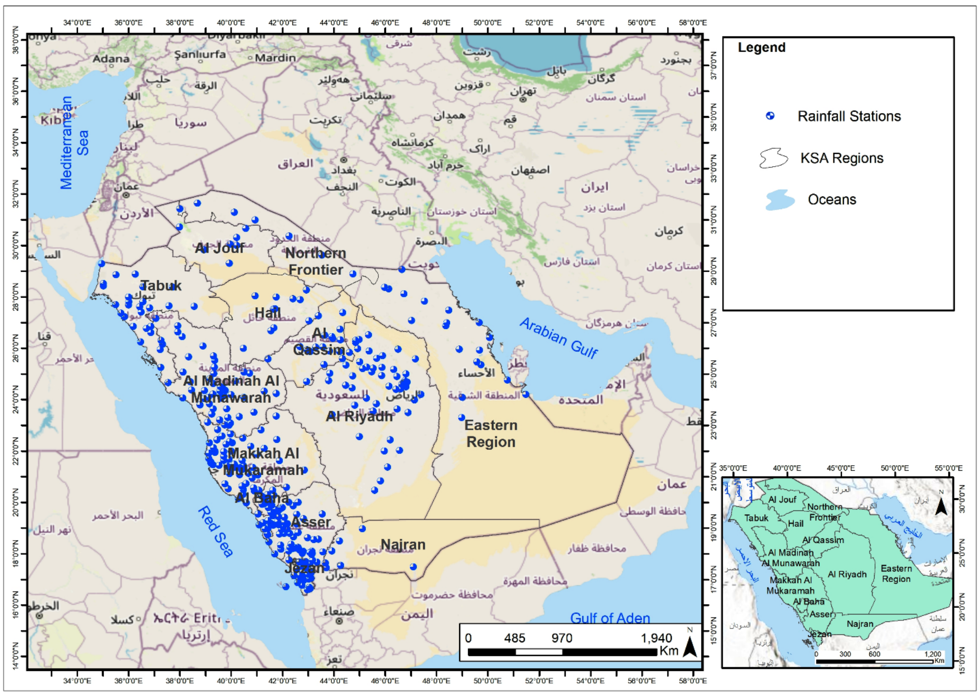

Figure 1. Location of MEWA Hydrologic Network Stations Recorded During "Madar 22 Event".

4. Results and Discussion

4.1. Spatial Distribution and Statistical Analysis of Rainfall During "Madar 22" Event

4.1.1. Spatial and Geographic Distribution of Rainfall

The "Madar 22" weather event commenced on Saturday, 23 July 2022, and persisted until Monday, 21 August 2022, spanning a duration of 30 days. During this period, precipitation was recorded by 360 rainfall and weather stations. "Madar 22" stands out as a significant and widespread event, affecting countries in the Arabian Gulf, Yemen, and various regions of the Kingdom of Saudi Arabia, including major cities such as Riyadh and Jeddah. This event brought intense and widespread rainfall, particularly to the western and central parts of the Kingdom, resulting in flash floods in several areas.

Meteorologically, the "Madar 22" event was driven by a unique combination of synoptic-scale atmospheric processes that produced intense and widespread precipitation across the Arabian Peninsula. Its formation can be traced to the anomalous intrusion and extension of monsoon depressions from northern India toward the southern Arabian Peninsula. This incursion coincided with northward and eastward oscillations of the subtropical high-pressure system, which at times extended toward the Levant and, alternatively, toward Iran. These synoptic shifts established favorable conditions for the influx of moist tropical air, facilitating the development of easterly troughs that propagated westward from the monsoonal low-pressure center. Additionally, the presence of extremely high surface and boundary-layer temperatures across the Arabian Peninsula enhanced atmospheric instability. This thermal profile allowed the Intertropical Convergence Zone (ITCZ) to penetrate unusually far north into the Arabian Peninsula. The interaction between the ITCZ and pre-existing low-pressure systems formed a high-energy lifting zone, promoting deep convective activity and resulting in the development of cumulonimbus cloud systems capable of producing intense rainfall and flash flooding.

On 27 July 2022, several regions in the United Arab Emirates including Sharjah, Ajman, Ras Al Khaimah, Khor Fakkan Port, and Umm Al Quwain experienced unprecedented heavy rainstorms. Al Fujairah Port received over 221.8 mm of rainfall within 24 hours, resulting in significant damage in several areas. UAE authorities reported that the heavy rains in Al Fujairah on 27 July 2022 constituted the most intense rainfall recorded in the past 27 years, surpassing the previous record of 175.6 mm in Khor Fakkan in 1995. Additionally, Oman recorded rainfall exceeding 300 mm within a 24-hour period. The impact of "Madar 22" extended beyond the Arabian Peninsula, affecting approximately 21 provinces in Iran, including Tehran.

According to records from the Saudi National Meteorological Center, varying levels of rainfall have been observed in the Kingdom of Saudi Arabia during July and August since 1993, particularly in the central and eastern regions. For example, Al-Ahsa station in the Eastern Region recorded 19.4 mm of rainfall on 26 August 1993. During "Madar 22" event, Riyadh Region received 26.6 mm of rainfall on 31 July 2022 marking the highest August rainfall recorded in the Kingdom over the past 40 years.

4.1.2. Statistical Analysis of Rainfall

Isohyetal map depicting the accumulated rainfall received during the "Madar 22" event was generated, and the weighted rainfall depth for each region was calculated using the Spatial Analysis tool within the Geographic Information Systems (GIS) application as shown in **Figure 2**. Also, the weighted average rainfall depth (mm) in all regions during the "Madar 22" event was illustrated in **Figures 3–15**.

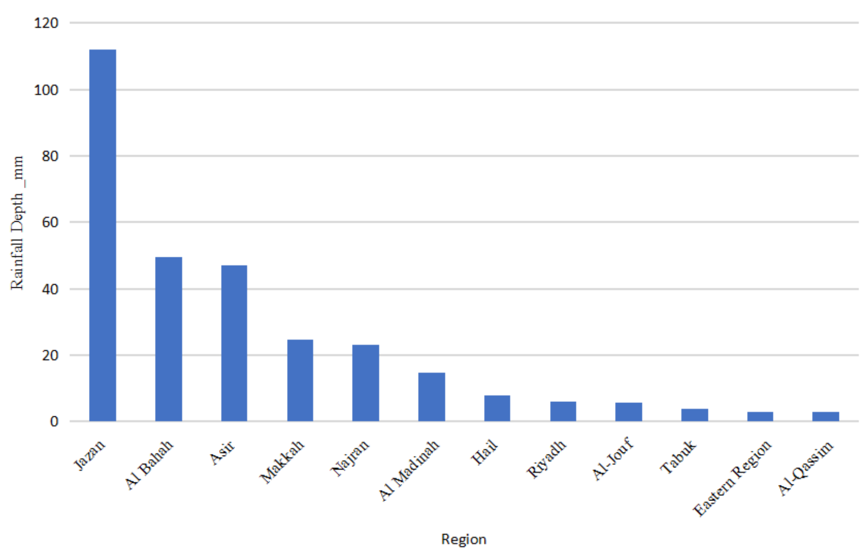

Figure 2. Weighted Average Rainfall Depth (mm) in the Regions During "Madar 22" Event.

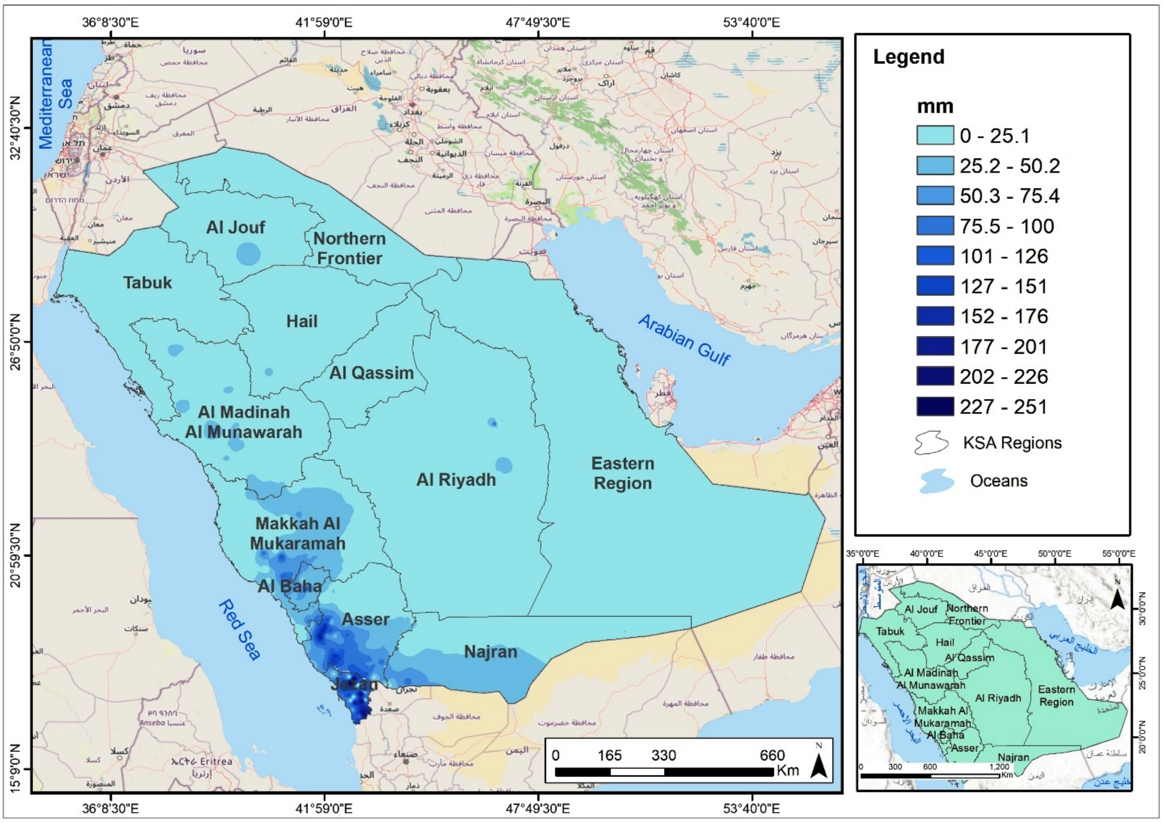

Figure 3. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over All Saudi Arabia.

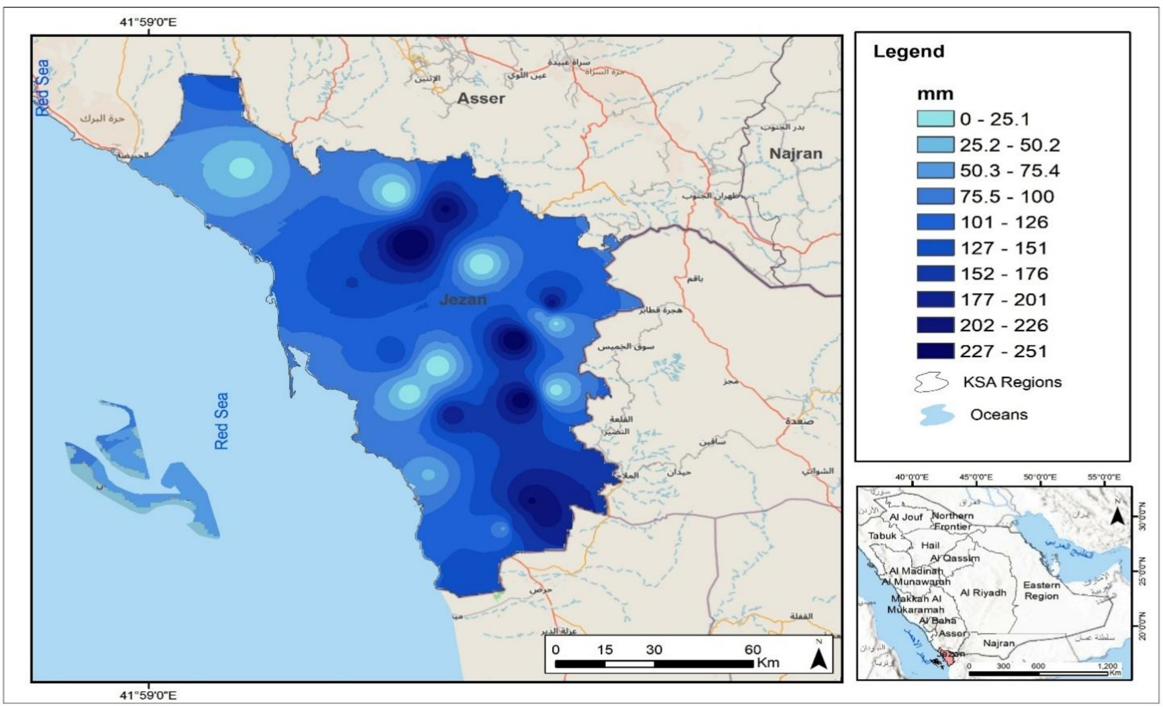

Figure 4. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Jazan Region, Saudi Arabia.

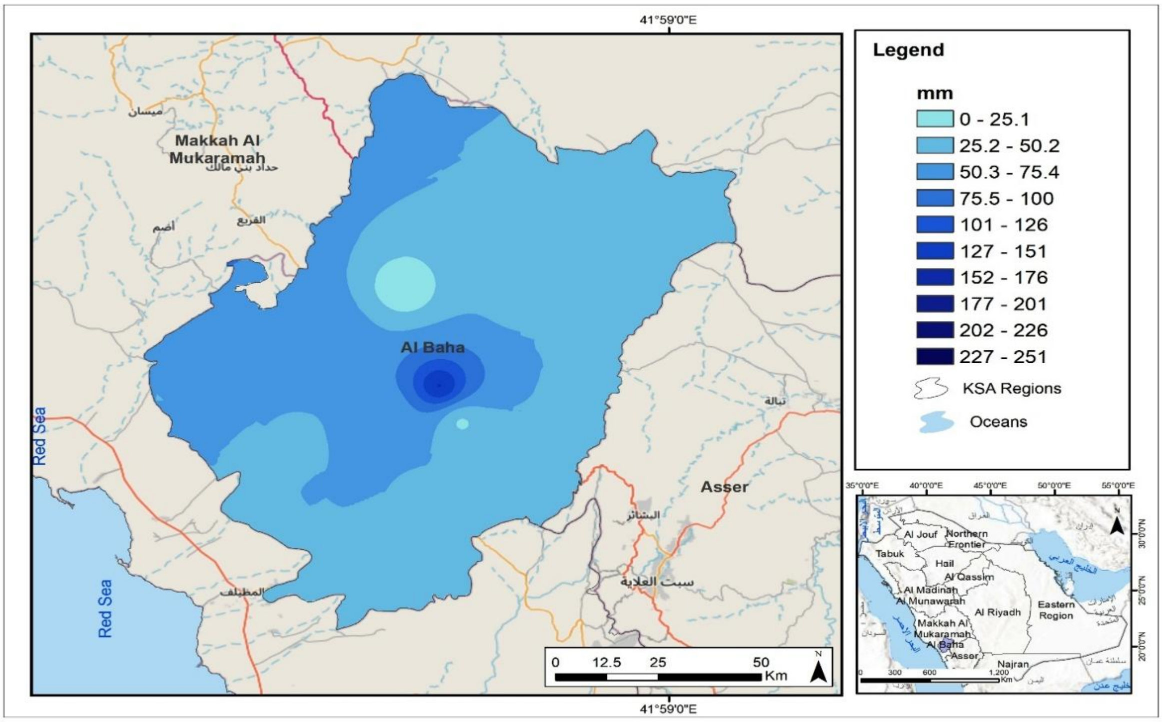

Figure 5. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Al Baha Region, Saudi Arabia.

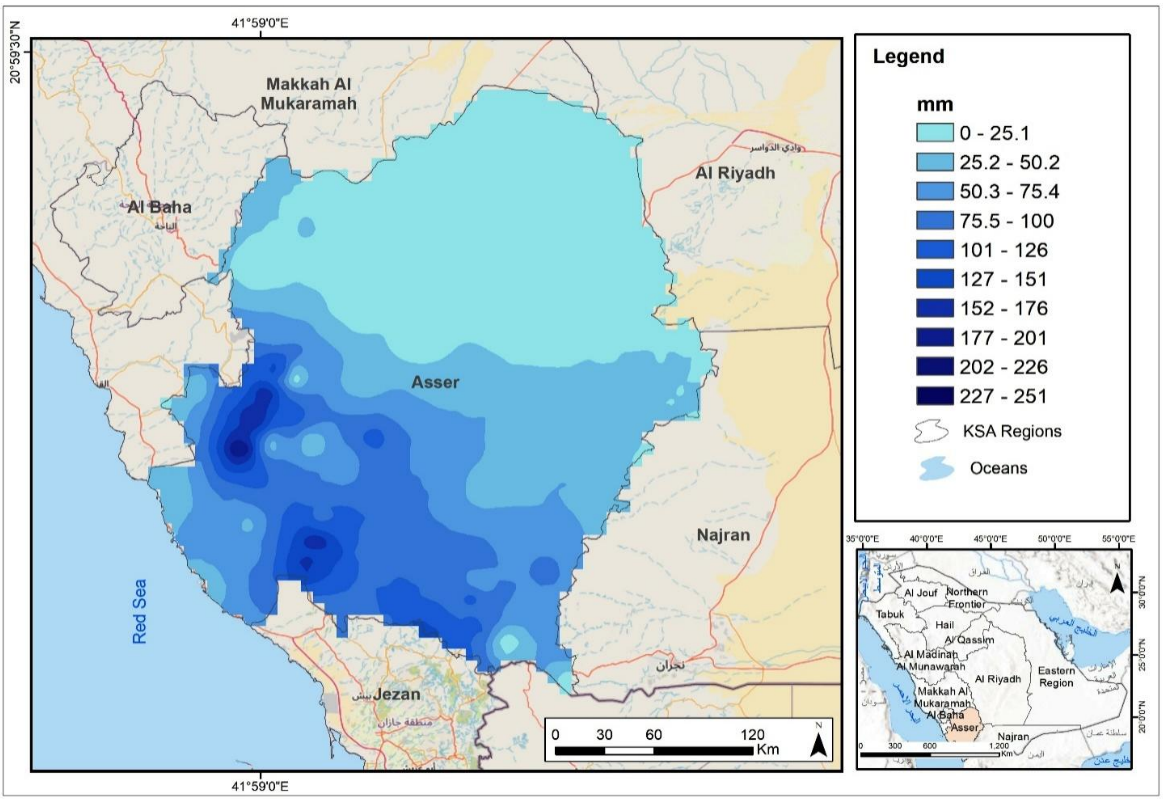

Figure 6. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Asir Region, Saudi Arabia.

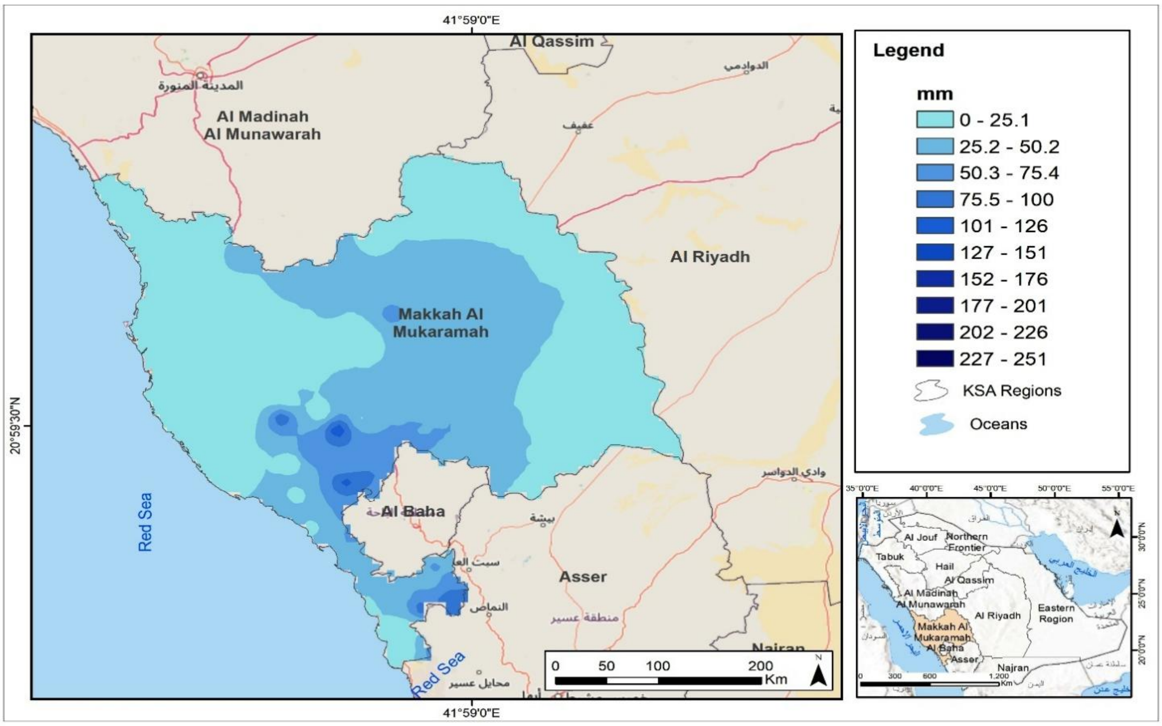

Figure 7. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Makkah Region, Saudi Arabia.

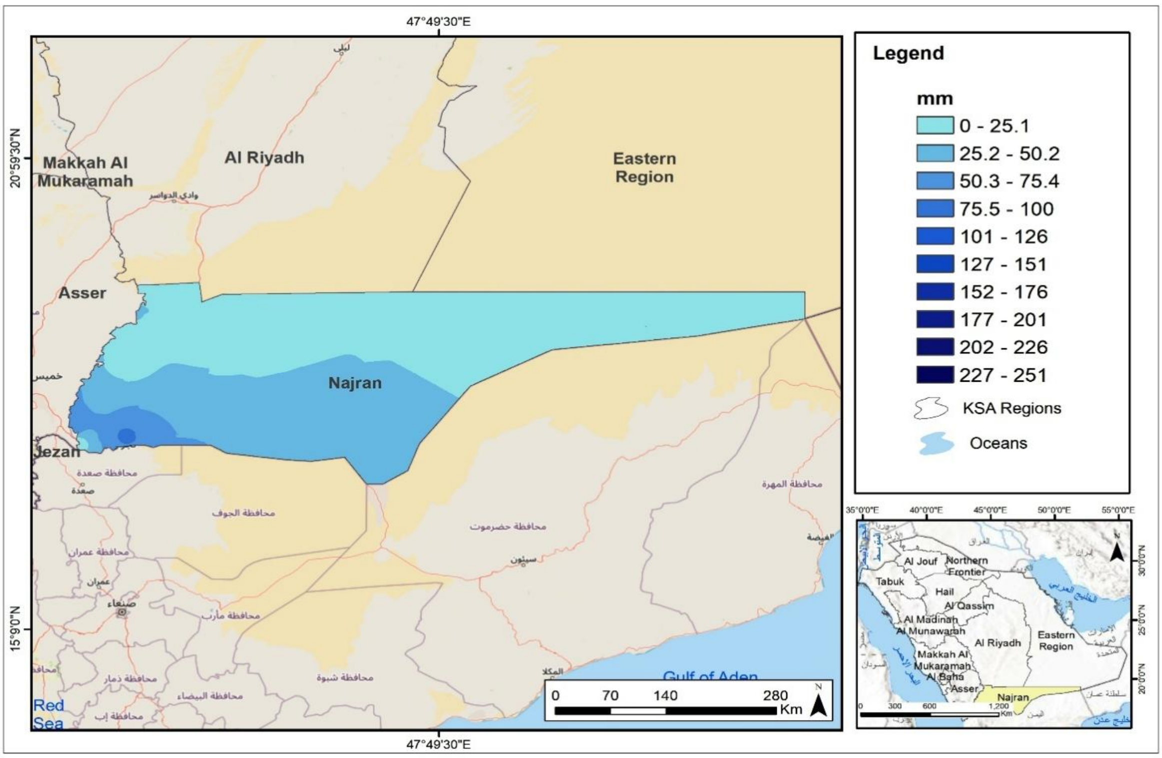

Figure 8. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Najran Region, Saudi Arabia.

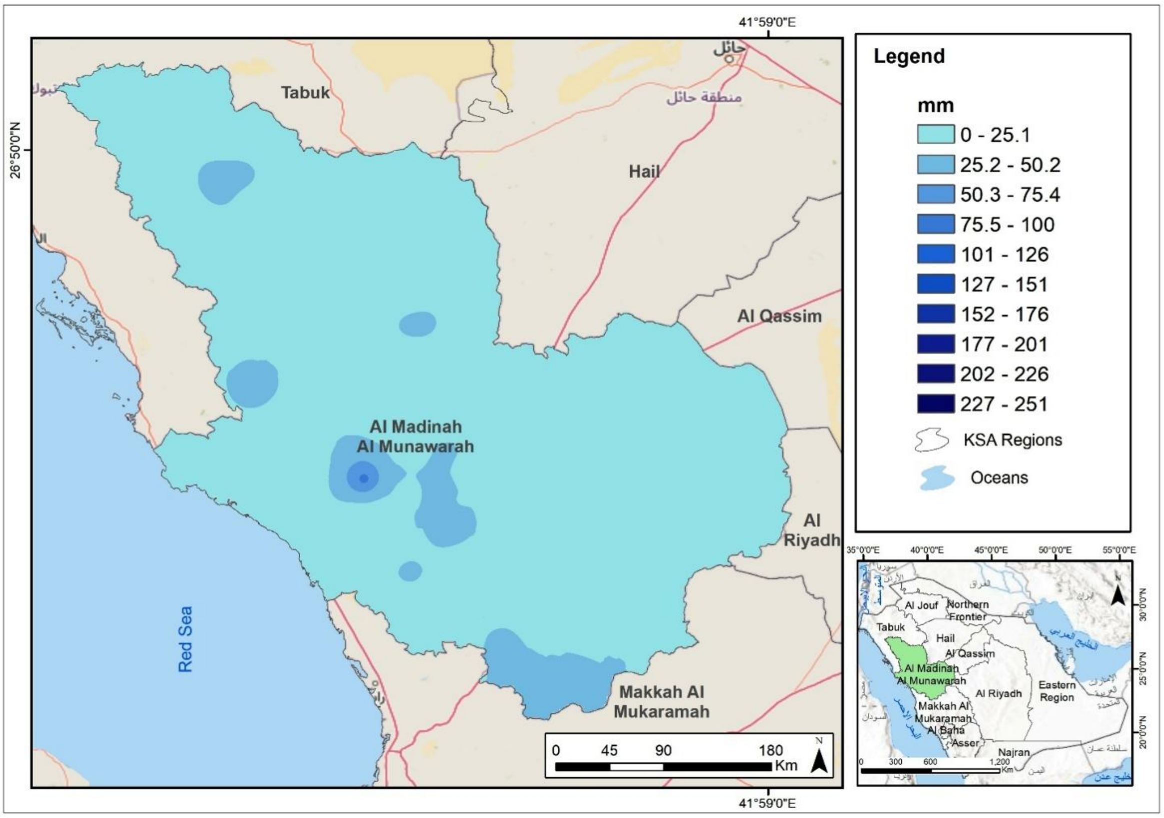

Figure 9. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Al Madinah Region, Saudi Arabia

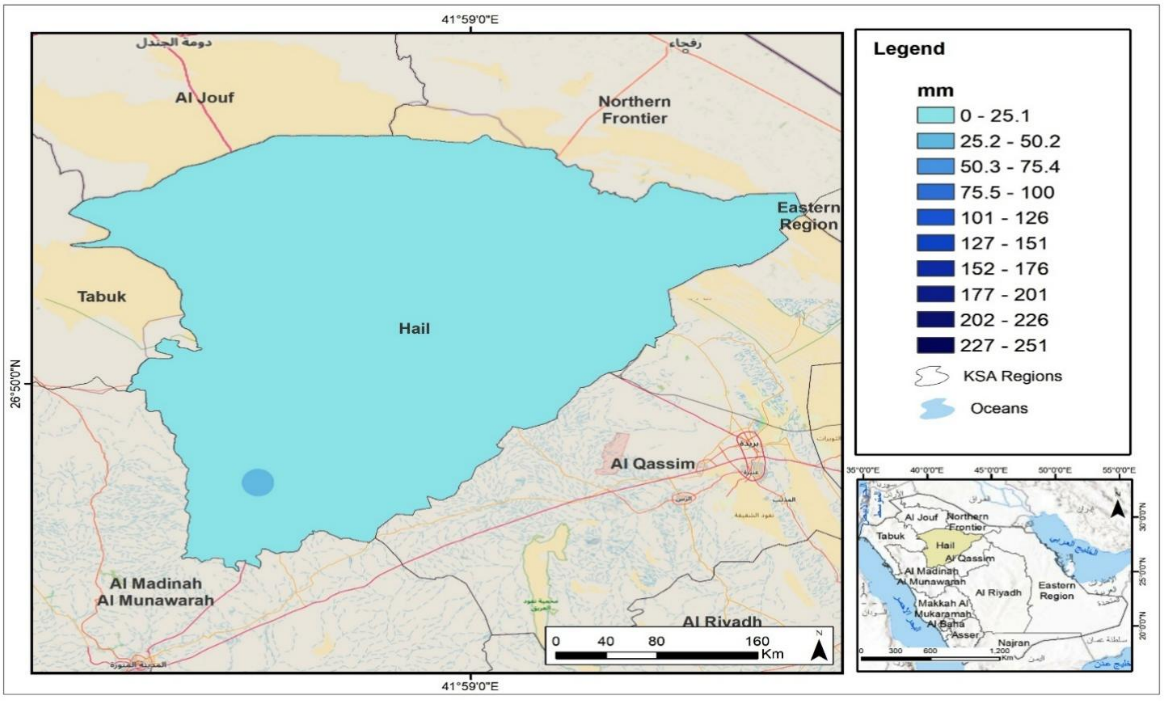

Figure 10. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Hail Region, Saudi Arabia.

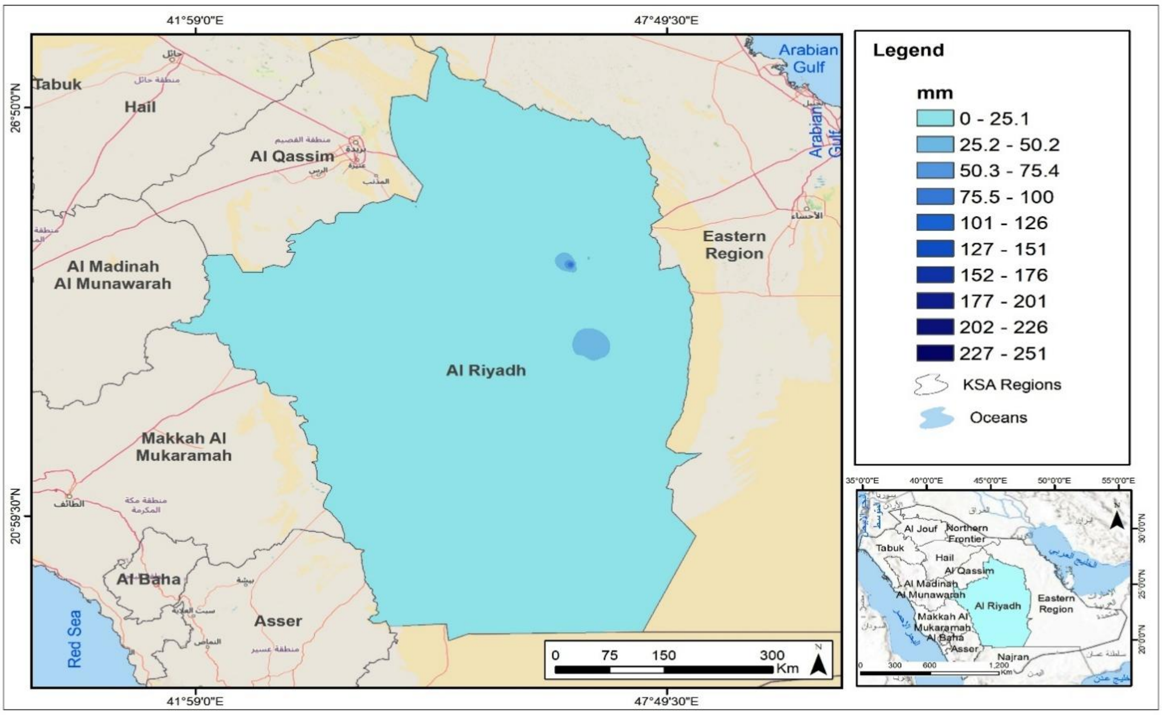

Figure 11. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Riyadh Region, Saudi Arabia.

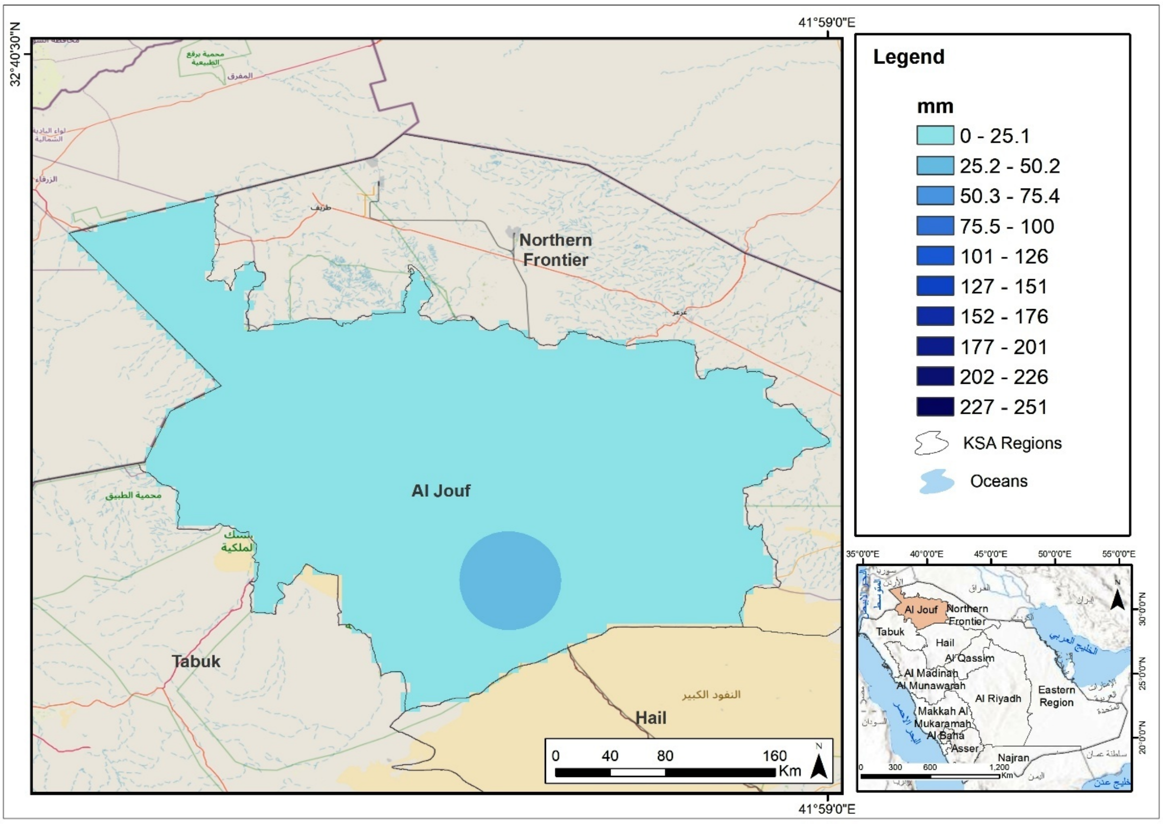

Figure 12. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Al Jouf Region, Saudi Arabia.

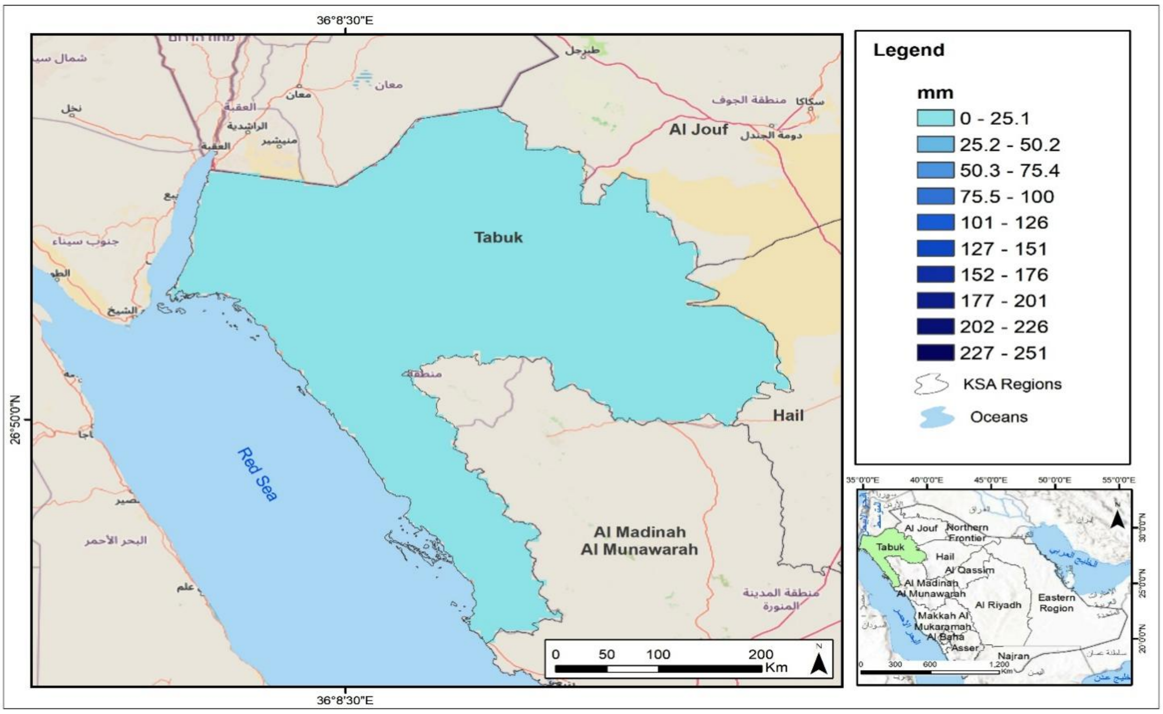

Figure 13. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Tabuk Region, Saudi Arabia.

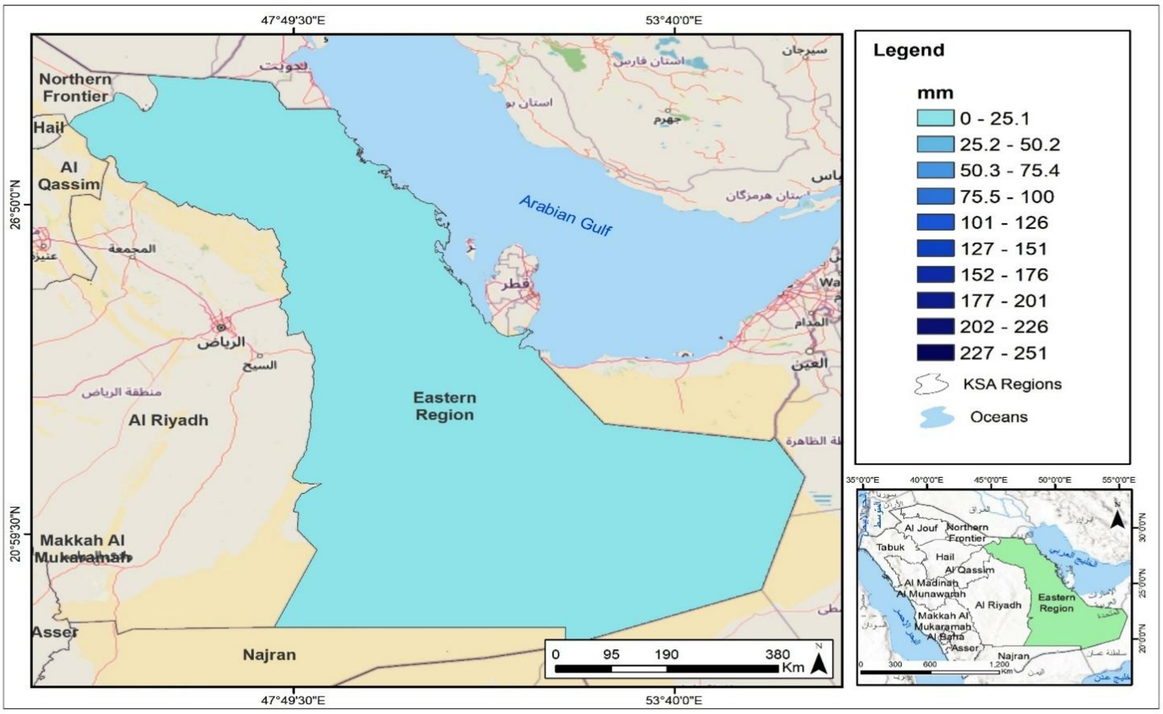

Figure 14. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Eastern Region, Saudi Arabia.

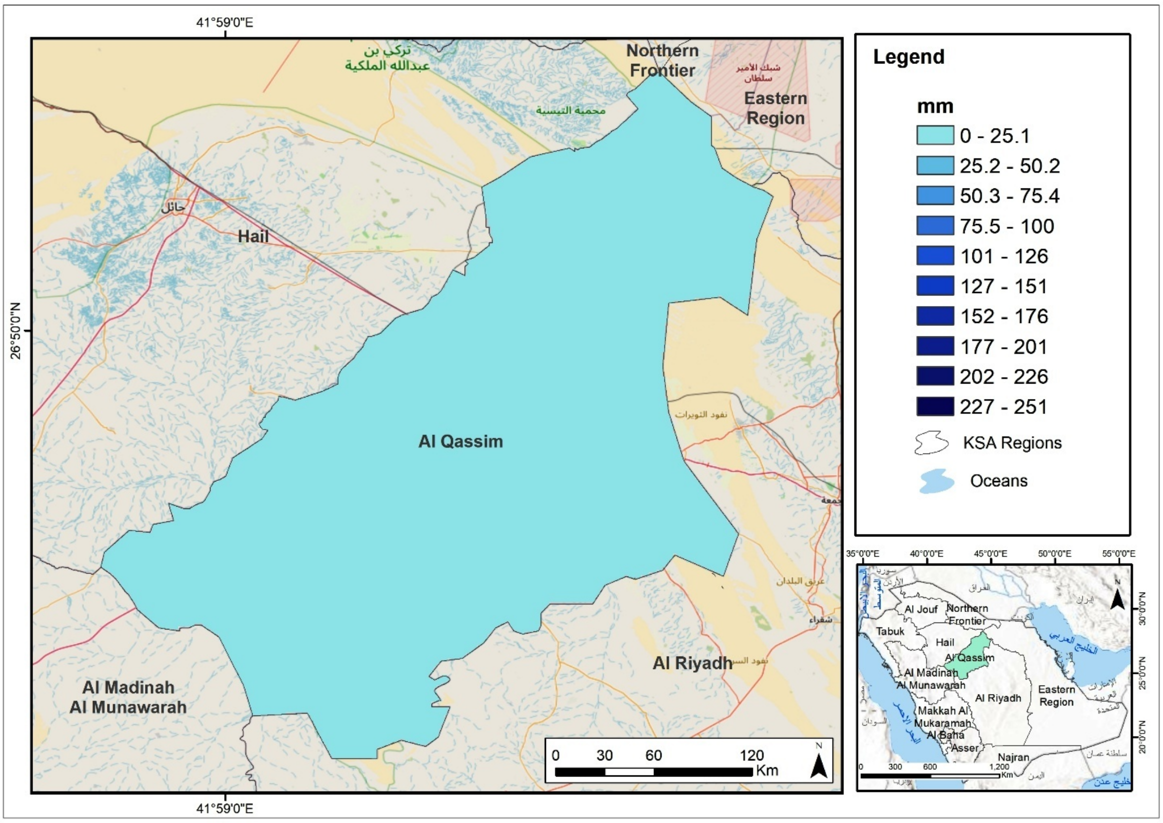

Figure 15. Spatial Distribution of Precipitation During the "Madar 22" Weather Event Over Al Qassim Region, Saudi Arabia.

In the present study, the spatial analysis results revealed that the average weighted rainfall depth across all regions of the Kingdom of Saudi Arabia amounted to 23.26 mm. This represents approximately 23% of the average annual rainfall depth for all regions over a 50-year period as estimated by Al Qahtani and Mattar (**Table 2**)[3]. Utilizing rainfall data from the MEWA hydrological network and ArcGIS-based spatial analysis, the event was found to deliver extreme precipitation equivalent to a 10-year return period for a 3-hour storm as concluded by Ewea et al.[5]. Furthermore, the analysis indicated that the Jazan region recorded the highest weighted rainfall depth at 111.97 mm, constituting approximately 41% of its average annual rainfall over the 50-year reference period. Al Baha region followed, with a recorded weighted rainfall depth of 49.51 mm, which accounts for approximately 25% of its average annual rainfall over the same period.

Table 2. Comparison Between the Average Annual Rainfall Depth Over a 50-Year Record and the "Madar 22" Event.

Region	Average Annual Rainfall Depth (mm) over 50-year Record	Average Rainfall Depth (mm) during "Madar 22" Event	Ratio of Average Rainfall Depth (mm) during "Madar 22" Event to The Average Annual Rainfall Depth for 50-year Record
Riyadh	85	5.98	0.07
Makkah	100	24.81	0.25
Al Madinah	53	14.77	0.28
Eastern Region	50	3.05	0.06
Asir	210	46.96	0.22
Najran	75	23.29	0.31
Jazan	275	111.97	0.41
Al Jouf	40	5.86	0.15
Northern Borders	60	1.32	0.02
Al Qassim	90	3.00	0.03
Tabuk	35	4.00	0.11
Al Bahah	200	49.51	0.25
Hail	70	7.79	0.11
Average	103.31	23.26	0.23

In addition to the analysis of weighted rainfall depth, the weighted rainfall volume received in each region of the Kingdom during the "Madar 22" event was calculated. The spatial analysis results revealed that the total weighted rainfall volume across all regions of the Kingdom of Saudi Arabia amounted to 20.605 billion cubic meters, representing approximately 18% of the total annual rainfall volume accumulated over a 50-year period. This estimation is based on a cumulative annual rainfall volume of 165.9 billion cubic meters, over the same period.

Moreover, the analysis showed that the Asir region recorded the highest rainfall volume during the "Madar 22" event, amounting to 3.630 billion cubic meters. This volume corresponds to approximately 24% of the region's total annual rainfall volume based on the 50-year historical record.

A detailed comparison between the weighted rainfall volumes recorded in each region during the "Madar 22" event and the corresponding 50-year average rainfall volumes is provided in **Table 3**.

Table 3. Comparison Between the Weighted Rainfall Volume During "Madar 22" Event, and the Weighted Rainfall Volume for the 50-Year Record.

Region	Affected Area (km^2)	Average Annual Rainfall volume for 50-year record (million m^3)	Average Rainfall volume during "Madar 22" (million m^3)	Ratio of Average Rainfall Volume during "Madar 22" to the Average Annual Rainfall Volume 50-year record
Riyadh	379,631	32,339	2,272	0.07
Makkah	139,924	16,846	3,472	0.21
Al Madinah	150,320	8,055	2,221	0.28
Eastern Region	540,438	47,077	1,651	0.04
Asir	77,297	15,390	3,630	0.24
Najran	129,761	11,213	3,022	0.27
Jazan	13,356	2,918	1,495	0.51
Al-Jouf	87,148	4,008	511	0.13
Northern Borders	101,482	7,826	134	0.02
Al Qassim	70,661	5,224	212	0.04
Tabuk	131,377	5,405	526	0.10
Al Bahah	11,076	1,984	548	0.28
Hail	117,086	7,584	912	0.12
Total/Average	1,949,556	165,869	20,605	0.18

(1) Maximum Daily Rainfall

Table 4 presents a comprehensive overview of the maximum daily precipitation recorded across various regions during the "Madar 22" event. Hamid El-Ulya station in Asir region recorded the highest daily rainfall, reaching 78.8 mm, underscoring the intensity and severity of the event. Following closely, Damad Dam station in Jazan region and Khamis Harb station in Makkah region reported 77.0 mm and 65.4 mm of rainfall, respectively. Other notable measurements include 44.0 mm at Al Ula station in Al Madinah region and 39.4 mm at Najran station in Najran region. The widespread variability of precipitation ranging from intense rainfall in Asir region to negligible amounts in Al Jouf and the Northern Borders regions highlights the spatial heterogeneity and extensive impact of the "Madar 22" event.

Table 4. The Maximum Daily Rainfall Precipitation in Regions During the "Madar 22" Weather Event.

Region	Maximum Daily Precipitation Depth (mm) During "Madar 22" Event	Station Name
Asir	78.80	Hamid El-Ulya
Jazan	77.00	Sad Damad
Makkah	65.40	Khamis Harb
Al Madeinah	44.00	Al Ula
Najran	39.40	Najran
Al Baha	37.60	Al Baha
Riyadh	33.60	Hutet Bani Tamim
Hail	19.40	Al_Haeit
Al Qassim	13.70	Al Shamasiya
Eastern Region	11.20	Al Damaam
Tabuk	4.20	Taymaa
Al Jouf	0.80	Talet Amaar
Northern Borders	0.60	Hazam Al Jalamid

Table 5 provides further insights into the maximum cumulative precipitation recorded during the "Madar 22" event. Al Baha Rainfall Station in Al Bahah region recorded a total of 151.4 mm, making it one of the most affected regions in terms of overall rainfall accumulation. However, Al Haqu station in Jazan region recorded the highest cumulative total, reaching an exceptional 276.2 mm. Additionally, Hamid El-Ulya station reported a cumulative rainfall of 200 mm. These statistics vividly illustrate the significant influence of the "Madar 22" event, not only in terms of daily extremes but also in overall rainfall accumulation over the event period. The data provide valuable insight into the hydrometeorological characteristics of the event, contribute to understanding regional climate variability, and offer a basis for improved forecasting and climate resilience planning.

Table 5. Maximum Accumulative Rainfall Precipitation During "Madar 22" Weather Event.

Region	Station Name	Maximum cumulative precipitation (mm) During "Madar 22" event
Jazan	Al Haqu	276.2
Asir	Hamid El Ulya	200
Al Bahah	Al Bahah	151.4
Makkah	Bani Saad	122
Al Madeinah	Faqra	79.6
Najran	Najran	79.5
Riyadh	Hutet Bani Tamim	33.6
Hail	Al_Haeit	26.2
Al Qassim	Al Naqra	18.2
Eastern	Sad Damad	12.9
Tabuk	Tayma	7.4
Al Jauf	Talet Amaar	0.8
Northern Borders	Hazam Al Jalamid	0.6

(2) Average Depth of Rainfall Precipitation

The "Madar 22" weather event left a significant hydrological imprint across the Kingdom of Saudi Arabia, meticulously documented through extensive data collection and analysis from various weather stations. Using the inverse distance weighted (IDW) interpolation method, the study quantified average precipitation depths during "Madar 22" event yielding valuable insights into the spatial impact of the event. This comprehensive analysis is visually represented in **Figures 4–8** and **Figures 10–15**, which illustrate the distribution of rainfall across Saudi Arabia during the event. The average precipitation depth across all the kingdom regions during the Madar 22" event was calculated as 23.26 mm. This value becomes particularly meaningful when compared to the long-term average annual precipitation depth of 103.31 mm, based on a 50-year historical dataset [13]. Such a comparison underscores the substantial impact of the "Madar 22" event within the context of the Kingdom's climatic history. A closer examination of regional precipitation patterns in Saudi Arabia during the "Madar 22" event, as illustrated in **Figure 3**, reveals that Eastern Region, Al Qassim, the Northern Borders, Al Jouf, Hail, and Riyadh recorded comparatively lower precipitation highlighting the selective nature of the event's impact. In contrast, Al Madinah, Najran, Makkah, Al Bahah, Jazan, and Asir regions experienced significantly higher rainfall depths (**Table 6**). Notably, Jazan region recorded an exceptional precipitation depth of 111.97 mm, which constitutes a substantial portion of its average annual rainfall of 275 mm. Similarly, Al Bahah received 49.51 mm of rainfall during this event relative to its average annual total of 200 mm. This integrated perspective is essential for future meteorological and hydrological planning, offering critical insights for strategic resource management and informed decision-making. The regional distribution of rainfall also emphasizes the variability of "Madar 22' event impact across the Kingdom. This disparity reflects the diverse climatic conditions across Saudi Arabia regions and highlights the localized nature of the event [10].

Table 6. Comparison Between the Average Precipitation (mm) Within 50-Year Record and "Madar 22" Weather Event.

Region	Average annual rainfall depth (mm) in the region within 50-year record	Average Precipitation (mm) in the region during "Madar 22" event
Riyadh	85	5.98
Makkah	100	24.81
Al Madinah	53	14.77
Eastern Region	50	3.05
Asir	210	46.96
Najran	75	23.29
Jazan	275	111.97
Al Jouf	40	5.86
Northern Borders	60	1.32
Al Qassim	90	3.00
Tabuk	35	4.00
Al Baha	200	49.51
Hail	70	7.79
Average	103.31	23.26

(3) Rainfall Analysis Over a 40-Year Record for July and August

An analysis of precipitation patterns in Saudi Arabia during July and August, based on a comprehensive 40-year climatological dataset (**Table 7**), reveals marked spatial and temporal variability across different regions of the Kingdom.

Table 7. Correlation Between Precipitation in July and August Over a 40-Year Record and "Madar22" Event.

Region	Average Precipitation in July (mm) over 40-Year Record	Average Precipitation in August (mm) over 40-Year Record	Total Average Precipitation in July and August (mm) 40-Year Record	Average rainfall depth (mm) in the region during "Madar 22" Event
Jazan	26.56	51.85	78.41	111.97
Asir	7.23	15.78	23.01	46.96
Al Bahah	5.42	10.83	16.25	49.51
Makkah	2.45	7.52	9.97	24.81
Najran	1.75	2.61	4.36	23.29
Al Madeinah	0.048	1.684	1.732	14.77
Hail	0.057	0.066	0.123	7.79
Riyadh	0	0.036	0.036	5.98
Al Jouf	0	0	0	5.86
Northern Borders	0	0	0	1.32
Eastern Region	0	0	0	3.05
Qassim	0	0	0	3.00
Tabuk	0.09	0	0.09	4.00
Saudi Arabia (Average)	3.35	6.95	10.31	23.26

In July, Al Bahah region exhibited a notable amount of rainfall, with an average of 5.42 mm, which is significant given the typically arid climate of the area. Jazan region, due to its geographic location and climatic characteristics, experienced a much higher average precipitation of 26.56 mm, affirming its classification as one of the more humid zones in the Kingdom. Asir recorded an average of 7.23 mm, a value that can be attributed to the region's elevated topography and the orographic effect, which often enhances precipitation.

In contrast, several regions including Al Jouf, the Northern Borders, Riyadh, the Eastern Region, and Al Qassim recorded no measurable rainfall, consistent with historical data indicating minimal precipitation during July in these areas. On a national scale, the mean precipitation depth recorded across the Kingdom in July 2022 was 3.39 mm, closely aligning with the long-term average of 3.35 mm for the same month over the 40-year historical period.

In August, precipitation levels increased significantly across most regions. Al Baha region recorded nearly a twofold increase, with average rainfall reaching 10.83 mm. Jazan region experienced a substantial rise to 51.85 mm, reflecting the intensified influence of the monsoon season. Similarly, Asir region saw a significant increase, with an average of 15.78 mm, further supporting the impact of monsoonal dynamics on summer precipitation in elevated areas.

Conversely, Riyadh region showed only a marginal increase in rainfall, registering 0.036 mm, while Al Madinah region recorded a modest rise to 1.68 mm. Although these increases were relatively minor, they indicate slight deviations from the typically dry conditions observed in historical records.

The mean precipitation depth recorded across the Kingdom in August 2022 was 10.86 mm, which notably exceeds the 40-year average of 6.95 mm for the same month. This observed increase illustrates a discernible trend toward higher precipitation during the latter part of the summer season. Such a pattern is consistent with long-term climatic observations across the Kingdom and underscores the seasonal intensification of rainfall associated with monsoonal influences over the past four decades.

(4) Precipitation Features of July and August 2022 in Saudi Arabia Regions

In June 2022, the Saudi National Center for Meteorology (NCM) issued a report detailing its climate forecasts and seasonal outlook for the Kingdom of Saudi Arabia for the summer 2022 spanning June, July, and August. The report predicted above-average rainfall in several regions across the Kingdom. These projections were subsequently validated by recorded data during the "Madar 22" event. For instance, the Jazan region recorded a significant increase in rainfall during July and August, reaching 111.97 mm substantially exceeding its 40-year historical average of 78.40 mm. Similarly, the Asir region recorded 46.96 mm of rainfall, nearly double its long-term average of 23.01 mm. Also, Makkah region experienced a marked increase, receiving a total of 24.81 mm, more than twice its historical average of 9.97 mm. Al Madinah received 14.77mm in Madar event exceeding its 40-year historical average of 1.73 mm in July and August. Hail, Riyad and Al Jouf regions have received (**Table 7**). Also, Najran, Hail, Riyadh, and Al Jouf regions received rainfall that were substantially above the 40-year historical averages for the months of July and August. Based on these findings, it can be concluded that the precipitation associated with the "Madar 22" event was significantly higher than the typical rainfall recorded in these regions during the same months over the past four decades. The convergence between the Center's forecasts and observed precipitation underscores the potential for enhanced integration of predictive tools into water resource planning and risk mitigation strategies. These insights contributed meaningfully to minimizing the impacts of the "Madar 22" event. Moreover, the comparison between forecasted and observed data highlights the increasing variability in Saudi Arabia's climate and reinforces the need for continued advancement in meteorological research, modeling accuracy, and forecasting technologies.

4.2. Spatial and Statistical Analysis of Surface Runoff Rates

4.2.1. Estimation of Potential Surface Runoff in Regions

Rainfall is a critical component of the hydrological cycle, affecting ecosystems, agriculture, and urban infrastructure. During rainfall events, soil saturation is gradually reached, infiltration rate decreases, where no additional water can infiltrate, and begins to accumulate on the surface as a surface runoff. Prolonged rainfall events alter the hydrological behavior of soils and watersheds by leading to soil saturation and increased runoff. Runoff is defined as the portion of rainfall that flows over the land surface towards wadies, streams, or rivers. The runoff coefficient (Rc) is defined as the ratio between precipitation and surface runoff. It is a critical parameter for estimating annual runoff volumes in watersheds, especially in semi-arid and arid regions such as the Kingdom of Saudi Arabia. Due to the Kingdom's complex geology and vast geographic extent, installing runoff gauges in all wadis is impractical. To overcome this limitation, various empirical formulas have been proposed to estimate the annual runoff coefficient for ungauged catchments based on data from gauged wadis. Among these, the empirical formula developed by Şen and Al-Suba'i is noteworthy [14]. Their study examined four gauged streams Wadi Baysh, Wadi Damad, Wadi Jazan, and Wadi Khulab in southwestern Saudi Arabia. The authors identified a linear relationship between the annual runoff coefficient and the catchment area. Sixteen gauged catchments across Saudi Arabia regions including Al Qassim, Al Madinah, Riyadh, Asir, Makkah, and Jazan were studied [15]. They applied linear regression techniques to estimate the mean annual runoff coefficients as a function of both mainstream slope and basin slope, with the mainstream slope serving as a key explanatory variable. In the present study, the authors developed empirical values for the regional potential annual runoff coefficient for each region of the Kingdom. The derived annual runoff coefficient values account for multiple factors, including region's geographic and geological setting, the general slope of the terrain, proximity to the Arabian Shield and Arabian Shelf, and the mean annual precipitation rates. The proposed runoff coefficient values were used to estimate the potential annual surface runoff depths and volumes over a 50-year period, as outlined in **Table 8**. The average annual surface runoff across the Kingdom during the 50-year period was estimated as 7,909 million cubic meters [13]. **Table 8** presents the estimated annual runoff coefficients and corresponding volumes for each region based on this long-term dataset. These average runoff coefficients were then applied to calculate runoff depths and potential surface runoff volumes specifically for the "Madar 22" event. The calculated runoff depths and volumes from "Madar 22" were compared to the estimated annual surface runoff volumes for each region based on the 50-year historical record. The total volume of surface runoff across all regions of the Kingdom during the "Madar 22" event was estimated at 1,058 million cubic meters, constituting approximately 12% of the total annual runoff volume accumulated over a 50-year span. Furthermore, spatial analysis revealed that **Asir region** recorded the highest potential surface runoff volume during the "Madar 22" event, totaling 290 million cubic meters, which represents 13% of the Kingdom's total potential annual surface runoff volume over 50-year record. **Makkah Region** followed with an estimated runoff volume of 278 million cubic meters, accounting for 17% of its own 50-year record. **Table 8** provides a comprehensive comparison of the potential surface runoff volumes recorded during the "Madar 22" event across each region, alongside their respective annual surface runoff volumes based on a 50-year record. The findings demonstrate a strong correlation between the spatial distribution of rainfall and runoff generation, particularly in regions with steep topography, higher rainfall intensity, and well-developed drainage systems. These results highlight the necessity of revising flood mitigation strategies, reservoir operation plans, and groundwater recharge management, especially in the face of increasing hydroclimatic variability linked to regional monsoonal activity and climate change.

Table 8. Correlation Between the Estimated Regional Potential Runoff Volume During "Madar 22" Event and the 50-Year Record.

Region	Annual Runoff Coefficient	Estimated Annual Runoff volume over 50-year record (million cubic meter)	Estimated Runoff volume during "Madar 22" (million cubic meter)	Ratio of Estimated Potential Runoff during "Madar 22" and Annual Runoff over 50-year record
Riyadh	0.03	912	68	0.07
Makkah	0.08	1,658	278	0.17
Al Madinah	0.02	330	44	0.13
Eastern Region	0.01	648	17	0.03
Asir	0.08	2,184	290	0.13
Najran	0.02	273	60	0.22
Jazan	0.12	527	179	0.34
Al-Jouf	0.02	102	10	0.10
Northern Borders	0.02	68	3	0.04
Al Qassim	0.03	394	6	0.02
Tabuk	0.02	190	11	0.06
Al Bahah	0.1	288	55	0.19
Hail	0.04	336	36	0.11
Total	0.05	7,909	1,058	0.13

4.2.2. Statistical Analysis of the Actual Surface Runoff Received in Dam Reservoirs

Using daily records of dam reservoir levels obtained from the Ministry of Environment, Water, and Agriculture (MEWA), the actual surface runoff volume that entered dam reservoirs during the "Madar 22" event was calculated and compared with the estimated annual surface runoff for each region. The total volume of runoff received within 189 constructed dams' reservoirs during the event reached **294.11 million cubic meters**, representing approximately **21%** of the total estimated surface runoff volume of **1,058 million cubic meters** during the "Madar 22" event across all the Kingdom of Saudi Arabia regions. This relatively low runoff harvested by dams indicates that nearly **79%** of the estimated surface runoff flowed through wadies and drainage networks. This shortfall can be attributed either to an insufficient number of constructed dams or to the deliberate diversion of surface runoff to support ecosystem and environmental balance. In response, this study recommends prioritizing comprehensive investigations of rainwater harvesting infrastructure across the Kingdom. Enhancing such systems would help to optimize the use of surface runoff and support groundwater recharge during future rainfall events. During the "Madar 22" event, **approximately 24 dams** spilled, including **9 dams in Najran region** alone. In contrast, **15 dams** received surface runoff for the first time, with **6 of these also located in Najran**, indicating the region's vulnerability to extreme precipitation. **Table 9** illustrates the harvested runoff volume into dam reservoirs, the number of dams that spilled, and the percentage of harvested runoff volume relative to the estimated regional surface runoff volume. The augmentation of dam storage during "Madar 22" has important implications for **water resource management** and **agricultural irrigation** systems in the Kingdom. The additional water supply necessitates strategic planning to ensure its optimal use, both to sustain agricultural productivity and to enhance **groundwater recharge** across affected regions. Notably, the **Jazan region** exhibited the highest impact, with **8 dams significantly affected by runoff**, in contrast to other regions with minimal influence. The data presented in **Table 9** can be utilized to evaluate the performance of existing dams and to inform enhancements aimed at increasing their resilience to future hydrological extremes. In addition to documenting the immediate effects of "Madar 22," the data offer valuable insights for long-term planning and the advancement of integrated water resources management.

4.2.3. Releasing of Dam Gates During "Madar 22" Event

During the "Madar 22" weather event, numerous dams across the southwestern regions of Saudi Arabia experienced significant daily surface runoff, resulting in reservoir water levels exceeding 75% of the respective spillway heights. In response to this critical hydrological condition, emergency operational protocols were promptly enacted, leading to the controlled release of water through the releasing of dam gates. This strategic intervention was instrumental in preserving the structural integrity of the dams while concurrently addressing the irrigation requirements of downstream agricultural zones and supporting groundwater recharge initiatives. Over the course of the event, a total of 70 dams were opened, discharging approximately 101.51 million cubic meters of water into downstream wadis across eight regions. Notably, in the Najran Region, 56.67 million cubic meters were released from 9 dams, while in the Makkah Region, 15.35 million cubic meters were discharged from 16 dams. Additionally, in the Jazan Region, 13.39 million cubic meters were released from 5 dams. For a detailed regional breakdown of the runoff volumes and the number of dams released during "Madar 22," refer to **Table 10**.

Table 9. Comparison Between the Harvested Runoff Volume in Dam Reservoirs During the "Madar 22" Event.

Region	Total harvested runoff in dams' reservoirs during "Madar 22" (million cubic meter)	Harvested total runoff during "Madar 22 Ratio"	Number of dams received runoff during "Madar 22"	Number of dams spilled during "Madar 22"	Number of dams received runoff for the first-time during "Madar 22"
Riyadh	12.07	0.18	16	0	0
Makkah	33.05	0.12	24	5	7
Al Madinah	6.37	0.14	23	5	2
Eastern Region	0.00	0.00	0	0	0
Asir	12.24	0.04	56	0	0
Najran	63.34	1.05	22	9	6
Jazan	146.73	0.82	8	5	0
Al-Jouf	0.00	0.00	0	0	0
Northern Borders	0.00	0.00	0	0	0
Al Qassim	0.00	0.00	0	0	0
Tabuk	0.05	0.01	2	0	0
Al Bahah	16.49	0.30	31	0	0
Hail	3.76	0.10	7	0	0
Total	294.11	0.21	189	24	15

Table 10. Released Dams During the "Madar 22" Event.

Region	Number of Released dams during "Madar22"	Volume of Released water from dams during "Madar 22" (million cubic meter)
Riyadh	9	4
Makkah	16	15
Al Madinah	10	3
Eastern Region	0	0
Asir	9	4
Najran	9	57
Jazan	5	13
Al-Jouf	0	0
Northern Borders	0	0
Al-Qassim	0	0
Tabuk	0	0
Al Bahah	5	5
Hail	7	1
Total	70.00	101.51

4.2.4. Comparison Between "Madar22" and "Rahw 2020" Summer Weather Events

In July and August 2020, the western and southwestern regions of the Kingdom of Saudi Arabia, along with parts of neighboring countries, experienced an extreme summer weather event locally known as "Rahw"[9]. Although "Rahw 2020" and "Madar 22" events occurred two years apart and impacted different regions, they exhibit several shared hydrometeorological characteristics that point to a broader regional pattern of intensified summer weather phenomena in the Arabian Peninsula. Both events occurred during the typically dry summer season and were driven by anomalous monsoonal activity originating from the Indian Ocean and Arabian Sea. These disturbances resulted in significant rainfall over short durations, triggering short-term hydrological extremes such as flash floods, elevated surface runoff, and in some cases, rising groundwater levels. A comparative analysis of the "Rahw 2020" and "Madar 22" summer weather events reveals both shared characteristics and distinct hydrometeorological differences. Although "Rahw 2020" was shorter in duration (18 days) compared to "Madar 22" (30 days), it exhibited higher average and peak rainfall intensities. The average precipitation during "Rahw 2020" was 32.56 mm, with a maximum daily rainfall of 83.10 mm and a total maximum cumulative precipitation of 306 mm, surpassing the corresponding values in "Madar 22" (23.26 mm, 78.80 mm, and 276 mm, respectively). However, "Madar 22" event had a far more extensive geographic reach, affecting 13 regions and a total area of 1,949,556 km², compared to 8 regions and 212,672 km² during "Rahw 2020." It also involved a greater number of recorded weather stations (360 vs. 193) and produced a substantially higher estimated total rainfall volume (20,605 million m³ vs. 10,894 million m³), despite its lower intensity. Hydrologically, "Rahw 2020" generated more runoff (1,308 million m³) than "Madar 22" (1,058 million m³), indicating more efficient conversion of rainfall to surface flow, likely due to localized intensity and terrain. In contrast, "Madar 22" saw a greater number of dams receiving runoff (189 vs. 165), though both the runoff volumes stored and released from dam reservoirs were higher during "Rahw 2020" (370 million m³ stored and 201 million m³ released) than in "Madar 22" (294 million m³ stored and 101 million m³ released).Both "Rahw 2020" and "Madar 22" event reflect shifting summer rainfall dynamics and emphasize the need for differentiated regional planning in flood risk management and infrastructure resilience. **Table 11** summarizes the correlation results between the two summer weather events [9], highlighting their differences in duration and geographic distribution. This comparison provides valuable insights into the varying impacts of these weather events on water resources in the region.

Table 11. Correlation Between "Rahw" 2020 and "Madar 22" Summer Weather Events [9].

Correlation Item	"Rahw 2020" Event	"Madar22" Event
Date started	24/7/2020	23/7/2022
Date completed	10/8/2020	21/8/2022
Duration (days)	18	30
Number of Affected Regions with the event	8	13
Total Affected area(km2) with the event	212,672	1,949,556
Number of Rainfall and Weather station recorded Rainfall	193	360
Average Precipitation (mm) during the event	32.56	23.26
Maximum daily Precipitation (mm) recorded during the event	83.10	78.80
Maximum Cumulative Precipitation (mm) during the event	306	276
The total Estimated Rainfall volume during the event (million cubic meter)	10,894	20,605
The total Estimated Runoff volume during the event (million cubic meter)	1,308	1,058
Number of dams received runoff during the event	165	189
Total Runoff volume received in Dam reservoirs during the event	370	294
Total Runoff volume released from Dams during the event	201	101

4.3. Spatial and Statistical Analysis of Groundwater Recharge

4.3.1. Groundwater Recharge in Alluvium and Basaltic Aquifers During the "Madar 22"

In the present study, an analysis of groundwater levels in 170 observation wells located within alluvial and basalt aquifers across various regions of the Kingdom of Saudi Arabia was conducted. Specifically, groundwater levels were examined before and after the "Madar 22" weather event, focusing on July and August 2022. The analysis revealed a significant rise in groundwater tables in 65 observation wells distributed across several regions, including Riyadh, Makkah, Al Madinah, Al Qassim, Asir, Jazan, Tabuk, Najran, Al Jouf, and Al Bahah regions during the "Madar 22" event. This indicates the impact of the "Madar 22" weather event on groundwater recharge within these aquifers. The most notable increase in groundwater levels was observed in Al Baha Region, particularly in observation well no. BAWO00420, where the groundwater level rose from a depth of 3.16 meters (measured from ground level) on July 25, 2022, to 0.43 meters on August 31, 2022. This substantial rise underscores the significance of "Madar 22" event in replenishing groundwater resources in the region. **Figure 16** provides a graphical representation of the observed increase in groundwater levels in Al Bahah observation well no. BAWO00420, illustrating the temporal changes before and after the weather event. The analysis of observation well data across multiple regions during the "Madar 22" event revealed a net rise in shallow groundwater levels ranging from 0.03 to 2.73 meters. This variation was observed predominantly in alluvial and basaltic aquifers, reflecting indirect recharge resulting from substantial surface runoff and localized infiltration. The most significant rises were recorded in regions characterized by high precipitation intensity, permeable geologic formations, and proximity to wadies or dam release zones. **Table 12** summarizes the key findings, highlighting the regions where groundwater level increases were observed during the "Madar 22" event and the magnitude of these changes in selected observation wells.

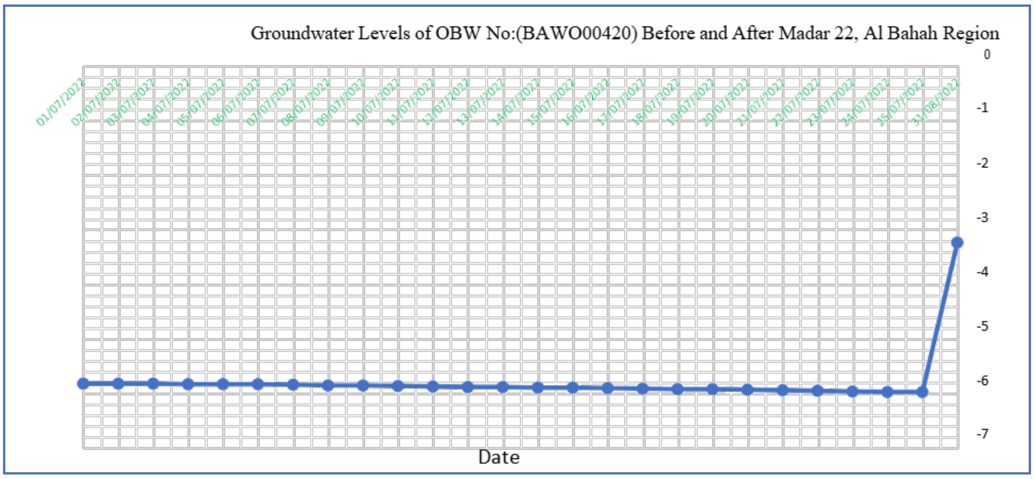

Figure 16. Groundwater Levels of Observation Well No:(BAWO00420) Before and After Madar 22, Al Bahah Region.

Table 12. Summary of the Net Rising Groundwater Levels in Alluvium and Basaltic Aquifers During "Madar 22" Event.

Region	Total Wells in Alluvium and Basaltic Aquifers	Recovered Wells During "Madar 22" event	Range of Net Rising in Groundwater Levels (m)	
			From	To
Al Bahah	12	6	0.410	2.73
Al Jouf	4	1	0.150	0.15
Northern Borders	1	0	0.000	0.00
Riyadh	12	3	0.860	1.26
Qaseem	2	1	0.800	0.80
Al Madeinah	44	22	0.050	1.58
Tabuk	9	5	0.040	0.07
Jazan	17	4	0.090	1.14
Hail	2	0	0.000	0.00
Asir	18	11	0.030	1.55
Makkah	41	8	0.040	0.65
Najran	8	4	0.130	2.64
Total	170	65		

4.3.2. Regional Groundwater Recharge in the Kingdom of Saudi Arabia

During the "Madar 22" weather event, a significant portion of precipitation contributes to groundwater recharge across the aquifers of the Kingdom of Saudi Arabia. The recharge process is influenced by multiple factors such as flood volume, duration, soil moisture content, and physical soil profile characteristics. In arid and semi-arid regions such as Saudi Arabia, groundwater recharge coefficients are typically low due to environmental conditions such as sporadic annual precipitation, limited plant cover, and low infiltration rates. Previous studies have provided insights into the recharge rates in different aquifers across the Kingdom of Saudi Arabia. For instance, Abdulrazzak et al., (1988) reported that 9–58% of mean annual runoff converts to recharge in various wadis of Saudi Arabia [16]. In central Saudi Arabia, the annual recharge rate to the Wasia Aquifer was estimated to be approximately 4 mm/year [17]. Similarly, recharge rates in arid zones are generally in the range of 2–4% of average annual precipitation [18]. In the case of the shallow alluvial aquifer in Wadi Wajj, located in western Saudi Arabia, the recharge was estimated to be as low as 0.48% of annual precipitation [19]. Additionally, the nonrenewable groundwater reserves in the Kingdom are estimated to be between 259.1 and 760.6 billion cubic meters, with natural recharge contributing to about 1.28 billion cubic meters per year [20]. The annual groundwater recharge to shallow aquifers in the Kingdom of Saudi Arabia was estimated as 3850 million cubic meters [21]. Quantification of groundwater recharge is one of the most important issues in hydrogeology, especially in view of the ongoing changes in climate and land use [22].

To estimate the potential groundwater recharge rates during the "Madar 22" event, empirical values for the potential annual recharge coefficient were introduced for each region of the Kingdom. The average total volume of groundwater recharge for all regions is calculated during the "Madar 22" event as 239 million cubic meters, representing 25% of the total volume of surface runoff during the event (**Table 13**). These estimated recharge coefficients align well with percentages reported by previous works [16,17,23–25]. These findings provide valuable insights into the groundwater recharge dynamics during extreme weather events like the "Madar 22" event, highlighting the importance of understanding and managing groundwater resources in arid regions like Saudi Arabia.

Table 13. Estimated Potential Groundwater Recharge in All Regions During the "Madar" Event.

Region	Ration of Potential Groundwater Recharge to Surface Runoff	Potential Groundwater Recharge Volume During "Madar22" (million cubic meters)	Ration of Potential Groundwater Recharge to Precipitation
Riyadh	0.27	18	0.008
Makkah	0.22	61	0.018
Al Madinah	0.28	12	0.006
Eastern Region	0.29	5	0.003
Asir	0.22	64	0.018
Najran	0.28	17	0.006
Jazan	0.18	32	0.022
Al Jouf	0.28	3	0.006
Northern Borders	0.28	1	0.006
Al Qassim	0.27	2	0.008
Tabuk	0.28	3	0.006
Al Bahah	0.20	11	0.020
Hail	0.26	9	0.010
Total	0.25	239	0.010

5. Conclusions and Recommendations

The "Madar 22" event is recognized as a rare and historically significant summer weather event due to its **wide spatial distribution** and **intensity**, which led to flooding across many parts of Saudi Arabia and neighboring Arabian Gulf countries. Daily data from rain and weather stations, along with observation wells, were used to generate spatial distribution maps of rainfall during "Madar 22" event. The **maximum daily precipitation** was recorded in **Asir region**, reaching **78.8 mm**, while the **weighted average precipitation** across all regions of Saudi Arabia was calculated at **23.26 mm** using **ArcGIS spatial interpolation techniques.**

The present study reveals that the mean precipitation depth across the Kingdom in August 2022 was 10.86 mm, significantly exceeding the 40-year historical average of 6.95 mm for the same month. This marked increase reflects a discernible trend toward heightened precipitation during the latter part of the summer season. Such a pattern is consistent with long-term climatological records across Saudi Arabia and highlights the seasonal intensification of rainfall linked to monsoonal dynamics observed over the past four decades. Prolonged rainfall events such as "Rahw 2020" and "Madar 22" fundamentally alter the hydrological behavior of soils and watersheds by leading to soil saturation and increased runoff. These processes have significant implications for flood risk management, soil conservation, and urban planning. Addressing these challenges requires a comprehensive understanding of infiltration dynamics, soil properties, and land-use interactions. The "Madar 22" event was compared to the "Rahw" summer weather event, which characterized by higher rainfall intensity and relatively limited spatial extent. In contrast, the "Madar 22" event exhibited a broader geographic distribution but was associated with comparatively lower rainfall intensity. This contrast highlights the differing hydrometeorological dynamics of the two events and underscores the need for tailored regional adaptation strategies in flood risk management and water resource planning. Based on the findings and implications of the "Madar 22" summer weather event, the following recommendations are proposed by the authors:

The "Madar 22" event should be utilized as a benchmark in the design of stormwater management systems and flood mitigation infrastructure. It also serves as a critical case study for improving the classification and understanding of meteorological zones within the Kingdom of Saudi Arabia.

Operational and maintenance plans for dams across the Kingdom should be revised to account for the occurrence of severe summer weather events. This includes the integration of dynamic response protocols and adaptive strategies.

Continuous coordination between the Ministry of Environment, Water and Agriculture, (MEWA) Civil Defense, and regional emirates is essential. Real-time communication systems should be strengthened to issue timely warnings to the public regarding the risk of dam gate openings and potential flooding near wadis.

It is recommended that at least **50% of the total reservoir storage capacity** be maintained as available free volume during the rainy season. This buffer will enable dams to safely accommodate incoming runoff during extreme precipitation events.

Based on the meteorological characteristics of "Madar 22," the authors have the opinion that similar monsoonal depressions are likely to occur with **increasing frequency and severity** during the summer months in the Arabian Gulf region. This trend is expected to be exacerbated by climate change, underscoring the urgency of climate-resilient infrastructure and policy adaptation.

Author Contributions

Conceptualization, M.Y. and A.A; methodology, M.Y. and A.R; software, A.M.; validation, M.Y., A.A., and A.R.; formal analysis, M.Y. and A.M.; investigation, M.Y. and A.R.; resources, A.A.; data curation, A.M.; writing original draft preparation, M.Y and A.R.; writing review and editing, M.Y. and A.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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