Climatic impact on Rainfall Analysis in Al-Madinah Munawwara Region

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Abstract. Long-term changes in temperature and weather patterns are referred to as climate change. Climate change and rainfall distribution are inextricably linked to arid and semi-arid regions. Saudi Arabia is entirely located in arid and semi-arid areas, and the arid climate that covers the majority of Saudi Arabia is typically characterized by large temporal and spatial variations in rainfall distribution. The availability of long-term rainfall depth records would be beneficial for studying the impact of climate change. This study aimed to assess the impact of climate change on rainfall analysis based on rainfall data generated by the HYFRAN-PLUS model during 1960–1990 and 1990–2020. Four rain-gauge stations near the Al-Madinah Munawwara region, namely Al Faqir, Umm Al Birak, Madinah Monawara, and Bir Al Mashi, were chosen for statistical analysis. The 1990–2020 rainfall data showed a significant climate change impact on the rainfall analysis at the Umm Al Birak station that was greater than that of the 1960–1990 data. The results of this study provide useful information for water resource planners and urban engineers to assess water availability and create appropriate storage systems considering climate change since 1960.

Keywords: climate change, maximum daily rainfall, Saudi Arabia, Al-Madinah Munawwara region, HYFRAN-PLUS model

1. Introduction

There are many definitions of climate, but the most important is long-term average weather conditions, usually calculated over 30 years by calculating average temperature, atmospheric pressure, wind–solar radiation, and precipitation. According to Wladimir Koppen (1884), the world is divided into five climatic patterns based on temperature distribution and seasonal precipitation. The climatic patterns are tropical, dry, temperate, polar, and continental. [1–2]

Each pattern has characteristics that distinguish it from the others, such as the amount and distribution of rainfall, and effects of wind, humidity, and temperature on evaporation and transpiration. These climatic factors form the hydrological features of an area [3–4].

Climate, geology, and geography all play a role in determining the hydrological characteristics of arid and semi-arid regions. Meteorology is important in hydrologic problems such as determining the most likely maximum rainfall conditions for spillway design, forecasting precipitation for reservoir operation, and determining the most likely maximum winds over water surfaces (used to evaluate the resulting waves in connection with the design of dams and levees) [3]. Climate change is a risk to urban growth, wadies stream land use/land cover change, and in-depth examination of soil types in arid and semi-arid areas [4–5].

Most global and regional climate change studies and models show that temperature is rising while rainfall not only decreases but also becomes increasingly unreliable, and unpredictable extreme events such as droughts and floods occur at a high frequency [4] and [6–7].

Rainfall is one of the most important natural resources used as a direct/indirect input for fulfilling the water needs of crops, as well as an indirect input for meeting the water demands of housing, commercial, and industrial activities via surface and subsurface storage. It is vital to study the historical long-term annual and
seasonal rainfall of a region for overall water resource development on a wider time scale for any location. [8–10].

Water scarcity is a problem that affects not only the availability of water, but also the quality of available water. Climate change will contribute to water scarcity not only by increasing temperatures and extending drought periods, which put a strain on water demand and existing water resources, but also by degrading water resources through extreme precipitation events that carry pathogens and other contaminants into waterways via runoff and flooding [11].

Precipitation is one of the most important factors influencing the environment, agriculture, and design of hydraulic infrastructures. Rainfall analysis forecasts the highest, average, and minimal rainfall values that can be expected in specific catchments over a given time period [13].

This study aimed to assess the impacts of climate change on rainfall analysis based on two sets of rainfall data (1960–1990 and 1990–2020) generated by the HYFRAN-PLUS model. HYFRAN and HYFRAN-PLUS (hydrological frequency analysis) were used to fit the statistical distributions. They include several powerful, flexible, user-friendly mathematical tools that can be used for the statistical analysis of extreme events [14–15]. The objectives of the study were achieved by identifying information about the study area (Al-Madinah Munawwara region and Wadi Al-Aqiq), maximum daily rainfall data, and various climate factors and rainfall analysis. Specifically, this study addressed the following objectives: (1) to highlight the importance of studying the long-term rainfall data changes in rainfall analysis in water resources management, (2) collect, describe, and summarize rainfall data, and (3) determine rainfall depth and intensity values for different return periods using the HYFRAN-PLUS model. Finally, this study aimed to match the vision of the Kingdom of Saudi Arabia to harmonize sustainable development goals.

2. Methodology

This section presents the planned methodology to achieve the objectives of the study. The methodology was divided into four main categories: inception of the study, data collection, data analysis and processing, and results and discussion. The details of each step are summarized in the form of the flowchart shown in Figure 1.
2.1 Study Area

The Al-Madinah Munawwara region in KSA as shown in Figure 2 was chosen for this study for two reasons. First, Al-Madinah is a great urban city that attracts thousands of Muslims every year from all over the world.
to visit the place related to Prophet Muhammad. Second, this region is one of the most famous Madinah Wadis, Wadi Al-Aqiq, and contributes to water sources.

Fig. 2: Location of study area

2.2 Data Collection

Rainfall data were recorded by rain gauges (four meteorological stations) near the study area: Umm Al Birak (J112), Al-Madinah Munawwara (M00l), Bir Al Mashi (M 103), and Al Faqir (J109). Details of the stations are presented in Table 1. All collected data were daily 24-h rainfall data collected from the Ministry of Environment, Water, and Agriculture (MEWA).

| No. | Station              | Code No. | Longitude (°) E | Latitude (°) E | Altitude (m) | Data Period     | Analysis First Stage | Analysis Second Stage |
|-----|----------------------|----------|----------------|----------------|--------------|-----------------|----------------------|-----------------------|
| 1   | Umm Al Birak         | J112     | 39°14’          | 23°2’          | 210          | 1960–2020       | 1960–1990            | 1990–2020             |
| 2   | Al-Madinah Munawwara | M00l     | 39°35’          | 24°31’         | 590          | 1960–2020       | 1960–1990            | 1990–2020             |
| 3   | Bir Al Mashi         | M 103    | 39°35’          | 24°31’         | 660          | 1960–2020       | 1960–1990            | 1990–2020             |
| 4   | Al Faqir             | J109     | 39°42’          | 23°2.5’        | 682          | 1960–2020       | 1960–1990            | 1990–2020             |

2.3 Description of Data Analysis

This study considered two sets of maximum daily rainfall data, i.e. 1960–1990 and 1990–2020, collected at four rain gauge stations as shown in Table 2.
3. Results and Discussions

Statistical analysis of rainfall data aims to determine the maximum rainfall values for a certain period for different return periods using various statistical distributions. Because the available rainfall data are 24-h daily readings, the results of the statistical analysis of the rainfall data are the maximum daily rainfall depth (XT) for different return periods (T). As shown in Figure 3, the GEV method was the best statistical distribution method in the HYFRAN-PLUS model for the M001, M103, J109, and J112 stations.
The descriptive statistical analysis of the maximum daily rainfall is shown in Table 3. The maximum and minimum rainfall records differed noticeably; the maximum values at the four stations were recorded in the wet year of 1968, while the minimum values were recorded in the dry year of 1973 for the same station.

| Descriptive Statistical Analysis | Al Madinah (M001) | Bir Al Mashi (M103) | Al Faqir (J109) | Umm Al Birak (J112) |
|--------------------------------|--------------------|---------------------|----------------|---------------------|
| No. of Data (observations)     | 27                 | 30                  | 22             | 30                  |
| Minimum                        | 1.4                | 2.5                 | 4.3            | 1.5                 |
| Maximum                        | 140                | 89.6                | 66             | 57                  |
| Average                        | 28.2               | 21.9                | 20.7           | 20.6                |
| Standard Deviation (SD)        | 34.0               | 17.3                | 12.8           | 14.02               |
| Median                         | 16.3               | 17.3                | 21             | 16                  |
| Coefficient of variation (CV)  | 1.33               | 0.805               | 1.46           | 0.692               |
| Skewness Coefficient (CS)      | 2.0                | 2.32                | 1.96           | 1.18                |
| Kurtosis Coefficient (CK)      | 3.7                | 6.84                | 6.33           | 0.57                |

In Figure 4, the maximum daily rainfalls observed at the rain gauge stations are plotted for 1960–1990 and 1990–2020. The annual rainfall varied between 1.4 and 140 mm (1960–1990) and 1.5 and 89 mm (1990–2020). The average and standard deviation of the total rainfall in 1960–2020 were 28.2 and 34.0 mm, respectively. The average can be used to obtain an indication of the departure of the annual rainfall from the normal or to compare climatic regions.
Fig. 4: Maximum daily rainfall: (A) 1960–2090 and (B) 1990–2020
Figures 5, 6, and 7 present geostatistical analyses to explain the spatial patterns of precipitation and temperature in Saudi Arabia and the Al-Madinah Munawwara region and to show their relationships during the periods 1948–2014 and 2000–2021. Arid and semi-arid regions are distributed within the Earth’s surface (Figure 5). The Kingdom of Saudi Arabia is located entirely in arid and semi-arid zones extending to the north and south.

Fig. 5: Spatial distribution of arid and semi-arid regions of Earth (shaded) [16]

Fig. 6: Geostatistical analysis using the Giovanni model in KSA: (a) 1948–2014 and (b) 2000–2021
As shown in Table 4, the rainfall depth vs. return period for stations M001, M103, and J109 exhibited the impact of climate change with the values of rainfall analysis in the period 1960–1990 being slightly greater than those of 1990–2020. On the contrary, in the period 1990–2020, the Umm Al Birak (J112) station indicated a significant climate change impact on rainfall analysis that was greater than that during 1960–1990. This may be explained by the fact that the Umm Al Birak (J112) station is only 26 km from the coast of the Red Sea, and this is obvious at an elevation of 210 m above sea level as indicated in Table 1.
Table 4: Results of rainfall depth vs. return period for stations

| Return Period (T, Years) | Rainfall Depth (mm) | Al Madinah (M001) | Bir Al Mashi (M103) | Al Faqir (J109) | Umm Al Birak (J112) |
|--------------------------|---------------------|--------------------|--------------------|-----------------|---------------------|
|                          | 1960–1990 | 1990–2020 | 1960–1990 | 1990–2020 | 1960–1990 | 1990–2020 | 1960–1990 | 1990–2020 |
| 2                        | 19.2      | 17.6      | 10.6      | 17         | 18.7      | 23.1      | 9.5       | 20.2       |
| 5                        | 39.4      | 30.7      | 23.6      | 29         | 36.2      | 37.5      | 20.0      | 35.8       |
| 10                       | 52.7      | 41.1      | 34.3      | 38.4       | 47.4      | 46.7      | 26.7      | 47.9       |
| 25                       | 69.6      | 56.8      | 50.8      | 52.3       | 62.4      | 55.0      | 34.9      | 65.5       |
| 50                       | 82.1      | 70.5      | 65.6      | 64.2       | 73.2      | 66.0      | 40.8      | 80.5       |
| 100                      | 94.6      | 86.2      | 82.9      | 77.7       | 84.0      | 73.8      | 46.5      | 97.2       |

The results of this study include the following three limitations.

1. Several rainfall datasets for 1960–1970 were unavailable at the M001, M103, J109, and J112 stations.
2. The four stations do not represent the entire study area for rainfall distribution but characterize the Wadi Al-Aqiq region.
3. Optimum number of Al-Madinah Munawwara region and Wadi Al-Aqiq rain gauge stations:
   - The accuracy of the estimated mean areal rainfall over a catchment is directly related to the density of rain gauge stations within the area and the spatial characteristics of storms occurring within a region or watershed area. For arid and semi-arid regions, the U.S. National Weather Service [17] recommends that the minimum number of rain gauges, \( N \), for a local flood warning network within a catchment area, \( A \), is given by \( N = 0.73 A^{0.33} \), where \( A \) is in square kilometers [3]. Therefore, the existing rainfall stations in the study area (Al-Madinah Munawwara region and Wadi Al-Aqiq) were insufficient to determine the exact average areal rainfall. The area of Al-Madinah Munawwara region is 151,990 km²; therefore, the optimum number of rain gauge stations is 40, while the area of Wadi Al-Aqiq is 5,000 km² and requires 10 rain gauge stations in addition to the four existing stations.

4. Conclusion
   - The current study was developed to assess the impacts of climate change on rainfall analysis based on rainfall data of 1960–1990 and 1990–2020 generated by the HYFRAN-PLUS model in the Al-Madinah Munawwara region, Saudi Arabia. The following conclusions were drawn based on the results.
   - Climate change is a risk to urban growth and wadies stream land use/land cover change according to outcomes related to the Umm Al Birak (J112) rainfall station.
   - Statistical analysis of rainfall data aims to determine the maximum rainfall values for a certain period for different return periods using various statistical distributions.
   - The limitations noted herein should not be ignored when considering the results of the study.
   - This study contributes to the protection of Al-Madinah Munawwara City from the dangers of heavy rainfall and floods by Wadi Al-Aqiq.
   - The study results will provide helpful information to water resource planners, farmers, and urban engineers to assess water availability and create appropriate storage systems considering climate change from 1960 to 2020.
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