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Spatio-Temporal Rainfall Analysis at Wadi Fatima for Flood Risk Assessment

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Abstract: This paper presents a systematic approach for the analysis of rainfall data for flood risk assessment in arid basins. Wadi Fatima, which is located in the western part of Saudi Arabian, has been chosen as an example of such analysis. The systematic approach presented in this paper has the following steps: (1) daily rainfall is collected from the available stations in the study area, (2) frequency analysis is applied to the maximum daily rainfall depths, (3) the common probability distribution functions for extreme values are fitted to the data, (4) the best probability distribution function is selected based on the root mean square error (RMSE) criterion and (5) spatial analysis using GIS techniques is applied for mapping the isohyets of rainfall depths over the study area for different return periods. Generated maps are used for flood estimation procedure in the next stage. The analysis of rainfall data showed that the majority of the stations follow Pearson type III. Rainfall records at those stations on the lower part of the catchment follow Gumbel distribution. This analysis proofs that not all stations are Gumbel distribution as the common practice in the Kingdom of Saudi Arabia. Every station has its unique probability distribution. The spatial analysis showed that the upper part of the basin (eastern part) and the south western part have high potential of flood risk as the expected rainfall depths for different return periods are high in those regions. Therefore, protection schemes at these locations should be carefully designed to avoid flood risk in these areas.

Key words: Arid Basins · Flash Flood Risk Assessment · Rainfall Distribution Analysis · Statistical Analysis of Rainfall Data · Spatio-temporal Rainfall Analysis

INTRODUCTION

Flash flood risk assessment in arid regions is an important but a difficult task. The main reason for this difficulty is the scarcity of data in arid regions. Flood risk assessment is extremely important for watershed management (i.e. for the sustainable development of water resources and for protection from flood hazard and drought).

Few studies have been focused on this issue in the Arabian Peninsula. Since the sever events of 2009 and 2011 in Jeddah City, Saudi Arabia, public and scientific communities directed the attention towards this issue. In the literature, Al-Yamany (2004) focused on the hydraulic response of Wadi Fatimah basin however, detailed analysis of rainfall data was missing in this research. [2] has performed a hydrologic behavior and flood probability for selected arid basins in Makkah area, where Wadi Fatima is one of them. In his analysis, Subyani considered only two probability distributions (Gumbel and Log-person type iii) for the rainfall analysis, however, he ended up choosing Gumbel distribution without mentioning why Gumbel distribution has been selected.

Therefore, due to the lack of in-depth-scientific analysis of rainfall data in the literature for flood risk assessment in arid zone, this study proposes a systematic approach to analyze rainfall data in arid basins for flood risk assessment. The results of this study will be linked with rainfall-runoff modeling for runoff potentials estimation in arid basins. The systematic approach presented in this paper is ordered according to the following steps:

- Daily rainfall data is collected from available stations in the study area,

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- Frequency analysis is applied to maximum daily rainfall depths,
- The common probability distribution functions for extreme values are fitted to the data,
- The best probability distribution function is selected based on the root mean square error (RMSE) criterion,
- Spatial analysis using GIS techniques is applied for mapping the isohyets of rainfall depths over the study area for different return periods and
- Generated maps of previous step are used for flood estimation procedure in the next stage.

The Study Area and Data Collection: Wadi Fatimah lies between longitudes 39° 15` and 40° 30` E and latitudes 21° 16` and 22° 15` N as shown in Fig. 1 and has an area of about 4869 km^2.

Geologically, the study area comprises Precambrian basement complex, Tertiary sedimentary and the Quaternary alluvial deposits (Fig. 1). The Precambrian rock units in the study area covers 63.6 % of the total area that consists of Late-Proterozoic basaltic to rhyolitic volcanic and volcano-clastic and epi-clastics of primitive island-arc type, which have been multiply deformed and metamorphosed and injected by intrusive bodies of different ages and compositions [3]. The Tertiary sedimentary succession is exposed beneath a cover of flat-lying lavas and Quaternary deposits on 3.9 % of Wadi Fatimah area. It consists of clastic rocks dominated by sandstones, shale, mudstones, oolitic ironstones and occasionally conglomerates. Quaternary deposits cover large parts of the study area, about 22.5 %, with 2-20 m thickness range. These deposits basically occur in the main channels of Wadi Fatimah. The basic units of the Quaternary rocks are gravel, alluvial fan deposits, talus deposits, alluvial sands and gravels of wadi beds and some eolian edifices [4]. Basin delineation is performed using digital elevation models [5].

Eight rainfall stations data have been collected for the study area. The time series of the annual rainfall for six of these stations are presented in fig. 2. It is obvious from the figures that the rainfall pattern is different from one station to another; also it is clear that station J114 has showed many zeros that give some doubts about the reliability of such station. Fig. 3 shows a map of the spatial distribution of the annual average rainfall over the basin. There is a general trend of the rainfall from the upper part of the wadi where the average rainfall reaches 150 mm wherease, in the downstream area of the wadi the average rainfall goes down to 80 mm. The reason behind this variation is that the upper mountainous area of the wadi always receives higher amount of rainfall, while the lower area at the wadi outlet receives less rainfall.

MATERIALS AND METHODS

Data from rainfall stations surrounding the study area were used to develop the annual average rainfall contour maps. The analyses and diagnostic tests regarding these stations have been performed. One of these analyses is the frequency analysis for each individual station as well as regional spatial analysis. The available rainfall records contain data for about 40 to 45 years from six stations. For flood assessment, statistical analysis has been performed on the maximum daily rainfall values and then various probability distributions and tests were used to obtain estimated rainfall depths corresponding to different return periods. Several different frequency distributions

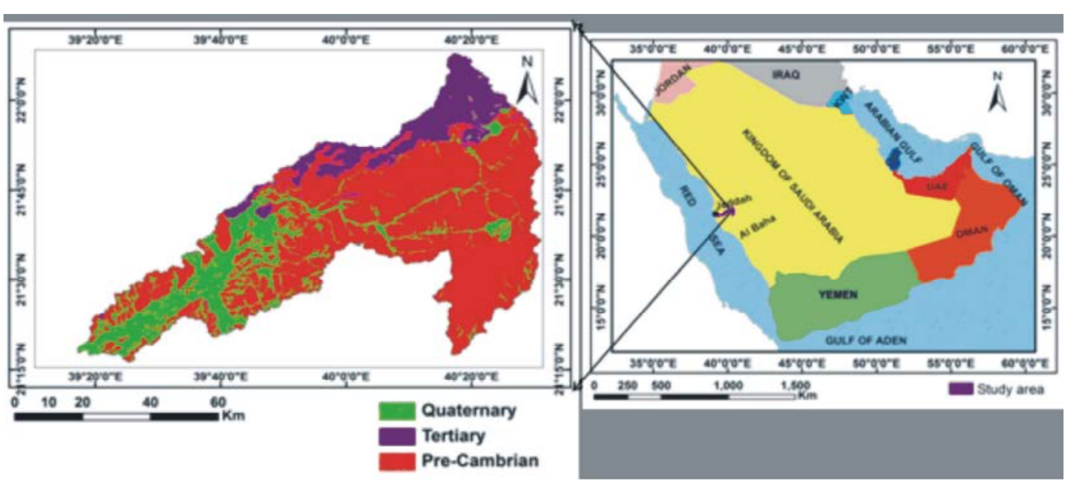

Fig 1: Location and geology of Wadi Fatimah basin [3].

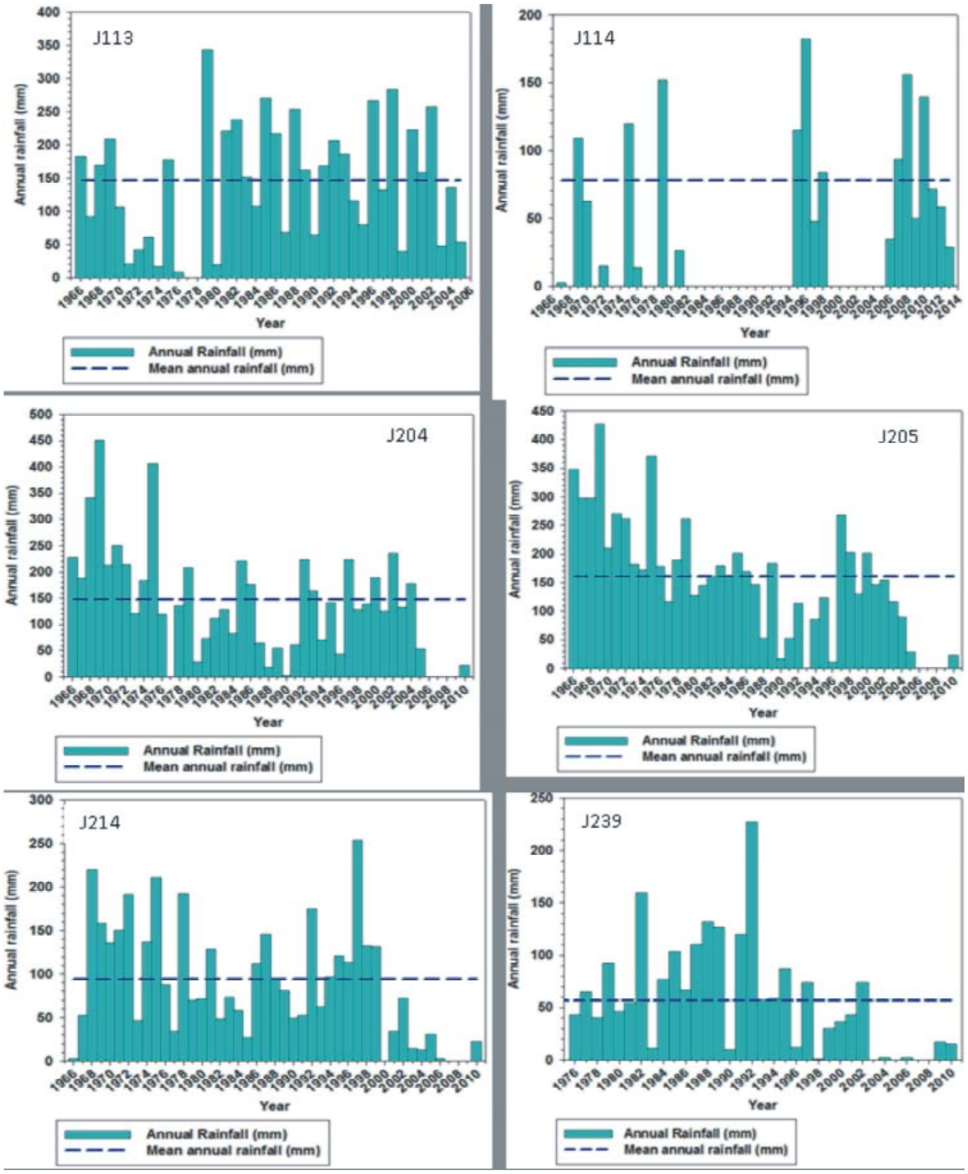

Fig 2: Time series of annual rainfall in wadi Fatimah.

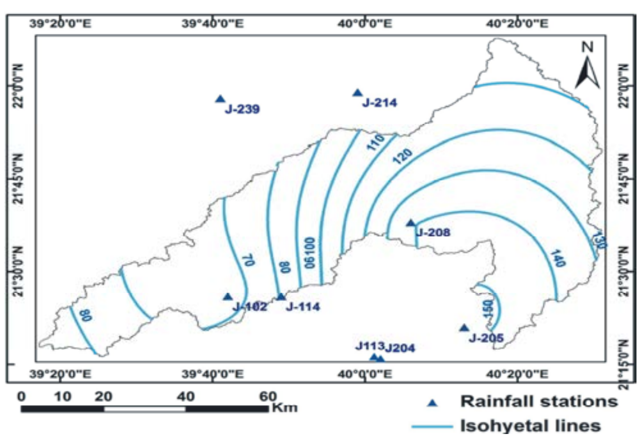

Fig 3: Spatial distribution of annual average rainfall Isohyetal Map of wadi Fatimah.

were fitted to the rainfall data at the stations to obtain the best distribution that well representing the data for each station. In this study, evaluated distributions are:

- Normal
- Gumbel
- 2-parameter Log-Normal
- 3-Parameter Log-Normal
- Pearson Type III
- Log-Pearson Type III

SMADA program was used to perform these tests. However, the best distribution is chosen based on the root mean square error criterion, RMSE [6] given by,

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\hat{R}_i - R_i\right]^2} \quad (1)$$

where,

- R_i is the observed rainfall depth at the station,
- $\hat{R}_i$ is the expected rainfall depth from the probability distribution and
- n is the number of data points at the station.

RMSE values for the various cases describe the average discrepancy between the expected and the observed values. Table 1 shows the best distribution based on the minimum RMSE as shown by the green cells in the table. Results from abovementioned analysis are presented in Figure 4. The figure shows the graphical representation of the rainfall depth at different return periods for the temporal analysis of rainfall data at the stations (based on the best probability distribution).

For the spatial analysis of the rainfall, the method of the inverse square distance weighting is used to map estimated rainfall for different return periods over the wadi area. A brief description of the methodology is given by Equation (2) [7].

$$P(x_0, y_0) = \sum_{i=1}^{m} w_i P_i$$

$$w_i = \frac{1/\mathbf{x}_i^2}{\sum_{i=1}^{m} 1/\mathbf{x}_i^2} \quad (2)$$

$$\mathbf{x}_i^2 = (x_i - x_0)^2 + (y_i - y_0)^2$$

Where,

- $P(x_0, y_0)$ is the estimated rainfall at coordinates (x_0, y_0)
- P_i is the rainfall at the given station i,
- w_i is the station weight and
- $x_i=(x_i, y_i)$ is the coordinates of the station.

RESULTS AND DISCUSSION

From the aforementioned analysis, it has been shown that stations J114 and J208 which are located on the southern part of the basin are following Gumbel distribution while, stations J102, J205 and J204 (also located in the southern part of the wadi) follow Pearson type III distribution. On the other hand, station J113 follows two-parameter log normal while the northern stations follow Pearson type III distribution. These results proof that the majority of the stations in the study area follow Pearson type III. The stations with Pearson type III distribution are the ones that are located outside the basin's boundary. However, the two stations J114 and J208 which are at the boundary are different. Figure 5 displays contour mapping of the rainfall distribution for different return periods (5, 10, 25, 50 and 100 years) based on the best probability distribution. The spatial analysis shows that the northern part of the basin and the south western part have high potential of flood risk since expected rainfall depths are high in those regions. Therefore, protection schemes at these locations should be carefully designed to avoid flood risk in these areas.

Table 1: Root mean square error of the rainfall stations at Wadi Fatimah.

	Stations							
Distribution Type	J 102	J 113	J 114	J 204	J 205	J 208	J 214	J 239
Normal	7.83	15.60	7.94	6.69	6.33	4.52	9.50	4.42
2 Parameter Log Normal	4.67	8.82	7.56	4.29	6.27	3.08	5.34	4.72
3 Parameter Log Normal	4.44	9.04	6.27	3.87	4.34	3.15	5.24	3.18
Pearson Type III	4.34	9.12	6.07	3.57	3.99	3.06	4.74	2.86
Log Pearson Type III	6.73	9.13	6.43	5.77	10.25	3.86	7.65	3.63
Gumbel Type I	5.00	10.61	5.08	3.96	4.63	2.92	5.91	3.13

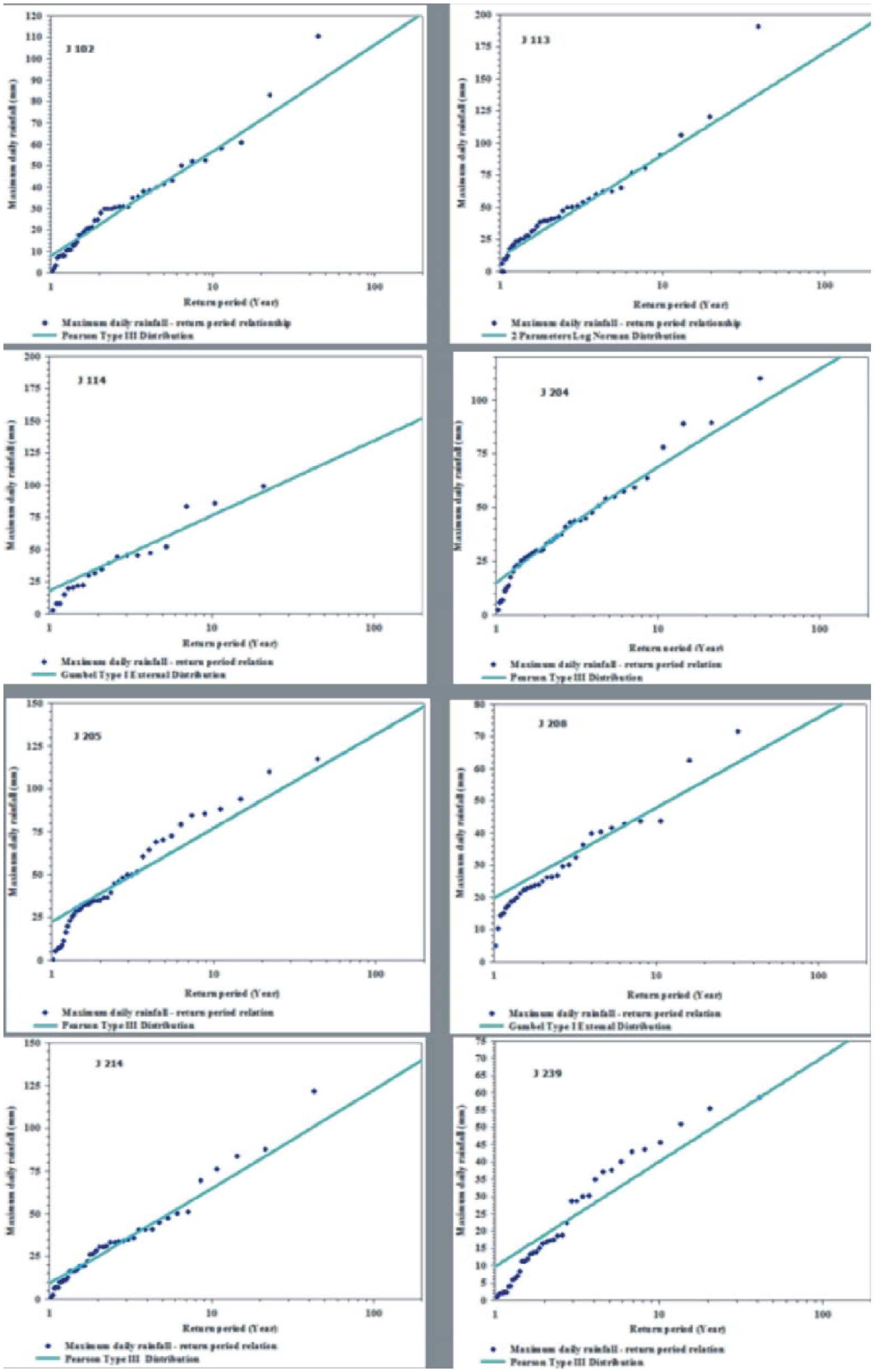

Fig 4: Graphical representation of the rainfall depth at different return periods for the temporal analysis of rainfall data at the stations (based on the best probability distribution).

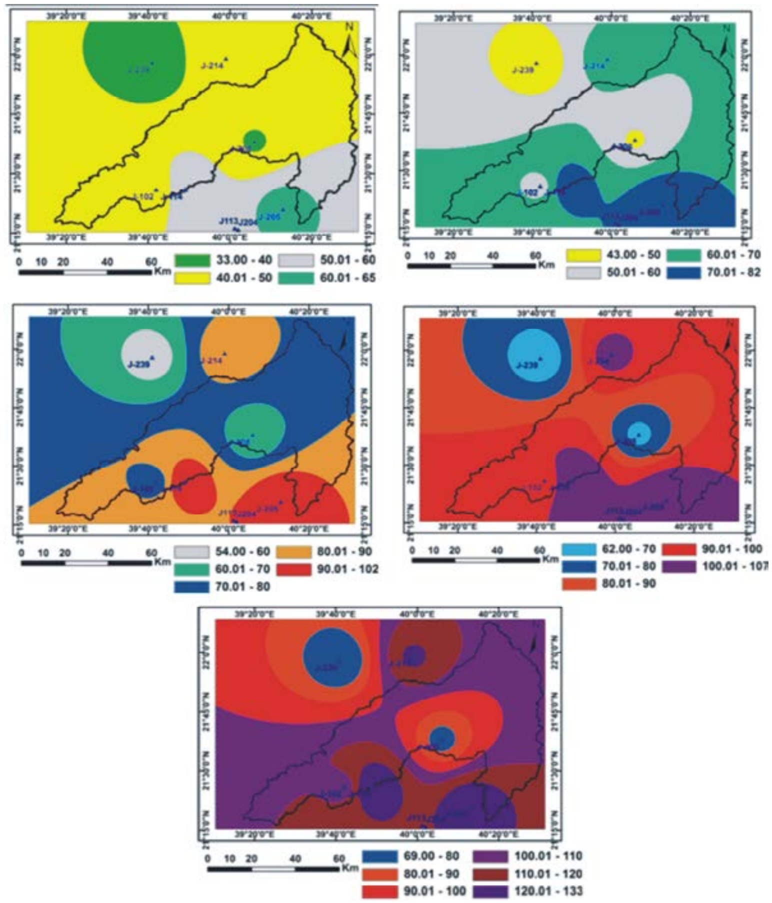

Fig 5: Mapping rainfall distribution for different return periods (top-left corner 5-years, top-right corner 10-years, middle left 25-years, middle right 50-years and bottom 100 years).

CONCLUSIONS

Analyzing rainfall data for Wadi Fatima as a basin in Arid Region for Flood Risk Potentials is an important work since flood events occurs frequently in the recent years and a considerable population accommodate the area. According statistical analysis, Pearson Type III is the common distribution of most stations.. The stations on the southern boundary of the catchment follow Gumbel distribution. This analysis proofs that not all stations are Gumbel distribution, which is the common practice in the Kingdom of Saudi Arabia. The spatial analysis shows that the northern part of the basin and the south western part have higher potential of flood risk since expected rainfall depths are high in those regions. Therefore, protection schemes and warning systems at those locations should be carefully designed to avoid the risk of casualties and property loss and distruction of facilities. Also, this study proofs the need for more rainfall data records in Saudi Arabia and more rainfall analysis for all basins especially big ones.

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