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ORIGINAL ARTICLE

Impacts of Climate Change on Water Engineering Structures in Arid Regions: Case Studies in Turkey and Saudi Arabia

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Abstract
The main concern of the paper is to provide a joint combination of probability distribution function, intensity–duration–frequency curves, and innovative trend templates under the climate change impact for better assessment of water resources systems design. The main purpose is to take currently employed approach in the design of water structures where the design variable features are derived from the complete hydro-meteorological records available; an approach is proposed where the time series is divided in half and applied. The results of the two approaches are then compared for two sites, one in southern Turkey and the other in western Saudi Arabia, using daily maximum rainfall records for more than 40 years. The features of the second half of the historical data are recommended to design water engineering structures. Climate change impacts give rise to increments of 5% (15%) over the classical approach in southern Turkey (western Saudi Arabia).

Keywords Arid region · Climate change · Design · Structure · Trend · Water

1 Introduction

Water resources system design, operation, management and maintenance are activities that are based on the hydro-meteorological variables so as to provide comfortability for the local settlements in particular and for regional social, economic and environmental activities, in general. It is well known that the social and economic development of a country is dependent on its water resources proper management against water shortages, floods, and droughts. Anthropogenic activities leading to climate change and variability play significant role in water resources activities presently and also in the future, and therefore, the climate change impact must be taken into consideration for any future planning. It has been already noticed by IPCC (2007, 2013) that climate change intensifies the hydrological cycle such that at some parts of the world, unexpected floods and especially flash floods take place; whereas in other parts, droughts and desertification events crepe slowly leading to damages on the society.

Currently, many centers of governmental water-related associations usually not consider climate impact effectively to their program quantitatively, although verbally the necessary precautions are cared for better adaptation studies. Especially, water resources systems must be managed and engineering structures (dams, canals, wells, etc.) must be based on refined methodologies that take into consideration the impact of climate change (Mohorji et al. 2017). Only properly designed water structures and their operation as well as management can serve a society for safe water supply and also for better agricultural products through an effective irrigation system. Any society or country should strive for food security, which depends on groundwater sources especially in arid lands, and therefore, groundwater recharge possibility through dams and injection wells must be applied with great care, where the role of climate change comes into view. In the future, present water supply systems, which are designed according to the traditional practices, are bound to come into the effect of climate change that should be adjusted to these structural units for better performance. Safe and reliable water resources providence is possible through the proper management of the present water resources system units. In particular, extreme weather events in summer and

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winter are leading to more frequent droughts and floods and causing more severe repercussions on water structures than in the past.

It is a challenge to various experts in water-related areas including meteorologists, hydrologists, water engineers and, last but not the least, the central and local administrators concerned with water supply and demand that the steady effect of climate change might increase, and therefore, the experts must search for innovative and adaptationally modified methodologies for better managements. The holistic approach must be thought; otherwise, improvement in one of the units in the water resources system might not add much to the complete performance of the system. For instance, any damage on the energy distribution network will have instantaneous effect on all the related services, which may cause a cascade of successive failures (RAE 2011). After all what have been stated above, the experts and especially water related engineers should care for least vulnerability, adaptation and if possible, mitigation against the climate change to protect the water resources in future.

To define resilience, some factors such as accommodate, absorb, recover and anticipate are used in a hazardous situation. To do so, the preservation, restoration, and improvement of existing infrastructure must be preserved for the sake of societal integration and along this line; policy-makers should care for new developments in the climate change impact possibilities in their area for better awareness and preparation against any undesirable event. It is preferable to depend on facilities of services and ecosystems as well as the natural resilience themselves. It has been observed that many societies and decision-makers do not care sufficiently for the points raised above or they have little experience and do not update the information sufficiently related to their problems (Şen 2015). Successful mitigation and adaptation against the changing climate are possible via resilience in related sectors to ensure the best solution, which is possible with the cooperation of all sectors so as to rule out the possibility of cascading failure.

There are large differences in the IPCC (2007, 2013) reports on climate impact as for the vulnerability of various water resource systems to climate change. Individual water impoundments in arid and semi-arid regions show sensitivity to climate change and most of them do not have a flexible adaptation methodology against the climate influence. Arnell (1999) reported the causative effect of that climate change in global average precipitation. It is expected that there will be an increase in evaporative demand, because of increasing temperature records as a result of climate change. Climate change will also impacts on the river flow reductions, and hence, water impoundments in the dams or in the aquifers. Such incidences are bound to appear more

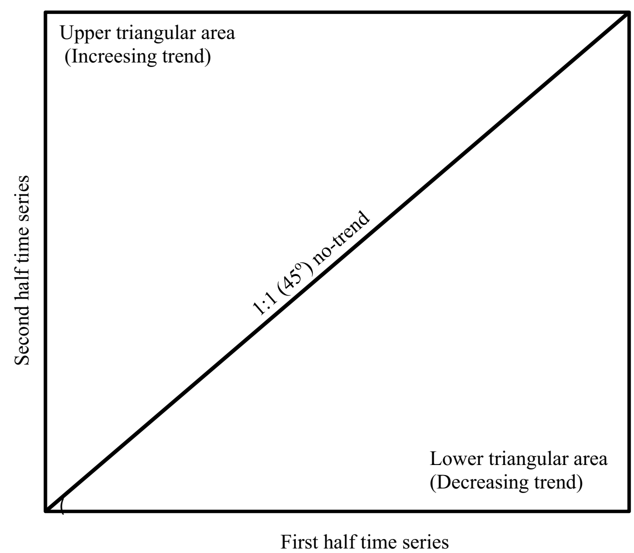
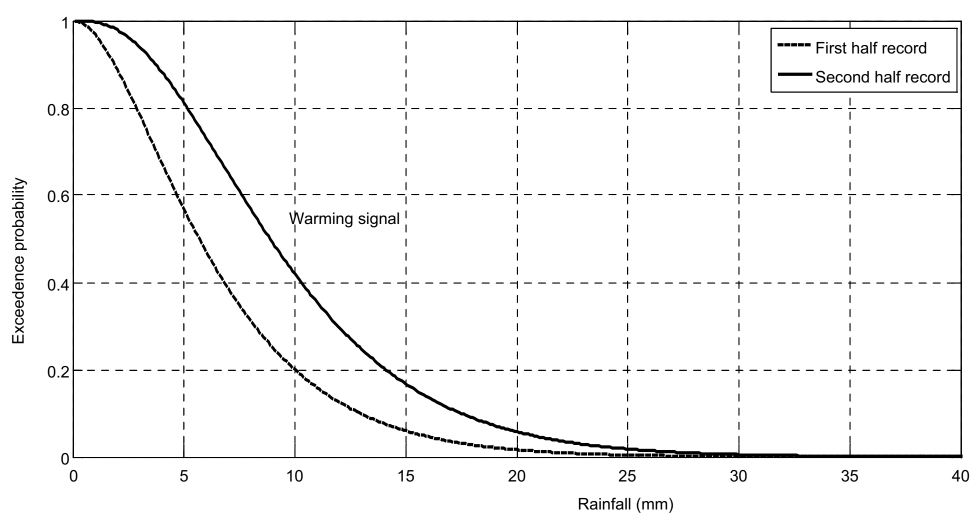


Fig. 2 Innovative trend template

Fig. 1 Global warming signature



effectively in the arid and semi-arid regions of the world, like the Arabian Peninsula.

Gleick (1998) wrote that the climate change is a major source of pressure on water resources and their management in future. Both demand and supply sides of water resources system components will take their share from the climate change impact negatively. If the necessary precautions are not taken from now, in the future, these impacts will show themselves in a more pronounced manner, which cannot be reversed easily causing economic losses. Kundziewicz and Somlyody (1997) and Kundzewicz et al. (2008) provided uncertainty studies in the climate change impact concerning water resource system management. Şen (2009) indicated that the climate change issues are concerned with different aspects of social, economic, engineering, scientific, cultural, and global problems, which need cost-effective solutions. As Keller et al. (2000) statement, in the twenty-first century, the one-third of the world will face water scarcity. It is the main goal of this paper to draw attention on water-related experts to climate change impacts on water structures and to the necessary methodologies to ensure a successful design.

2 Hydro-meteorological Variables

Meteorological and hydrological aspects of climate change are concerned with the precipitation change and variation as a result of evaporation increase. It is necessary to assess the amount of precipitation for water deficit periods and areas especially in arid and semi-arid zones. In case of even precipitation reduction, proper water resources structures (dams, canals, dykes, levees, wells, etc.) and effective management of available water reduce the possible negative effects on water supply problems. If, on the other hand, precipitation increases in some areas and decreases in others

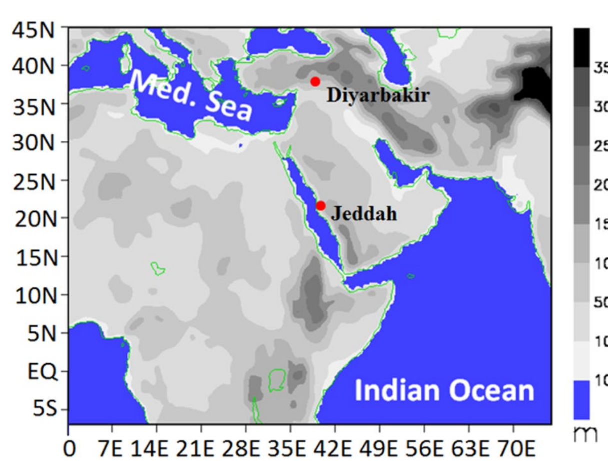


Fig. 3 Study area with location of meteorology stations used in Turkey and Saudi Arabia

(for instance see Almazroui 2013; Almazroui et al. 2016, 2017) this will create a need for efficient management programs to redistribute regional water resources to areas of high demand.

To do an effective water resources effective plan, spatio-temporal changes of precipitation estimations are very important by considering the hydro-meteorology-related aspects of land surface, water fluxes and earth energy cycle. The lakes, soil moisture, seasonal snow packs, glaciers, groundwater, and ice sheets are land surface while runoff, evaporation, precipitation, and groundwater recharge are water fluxes). For effective scientific and practical solutions, the variability of both the short- and long-term precipitation must be studied with projections based on different scenarios to better manage water engineering structures jointly in relation to land, oceans, and atmosphere.

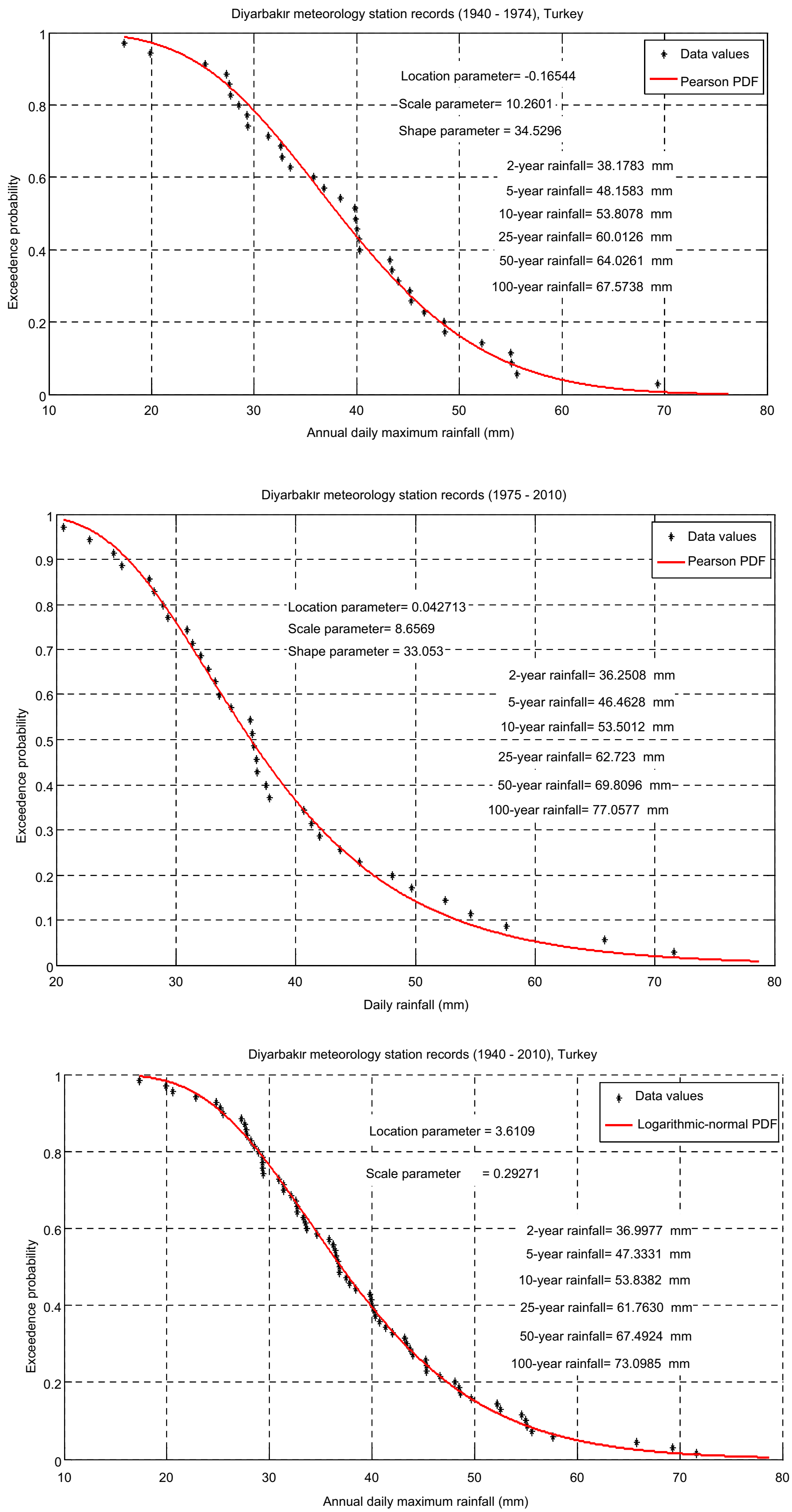
To reduce the uncertainty, the most important point is to relate global climate change and variability to regional scale for identifying the linkage between large-scale climate variability and regional conditions. For a specific region, the ability to project the consequences of global climate change to a specific region is now needed more than ever. For example, it is essential for decision-makers of long-range economic investments on water structures to have and update their information about vulnerability of hydro-climatic regimes.

It is possible to detect climate change through averages over relatively long periods such as 30 years; meteorology, as its main contributory factor, must be studied to improve projections. The basic data for proper water resources management are rainfall records, which provide surface and groundwater water storages. The regional records are central to any water engineering structure design. Provided that the rainfall records are available, then one can deal with them to obtain the probability distribution function (PDF), intensity duration frequency (IDF) curves and innovative trend template (ITT) indicators. The precipitation records help to calculate intensity, duration and risk (frequency) values. The life of a water structure (return period) is calculated on a 0.50 risk (2 years), 0.20 risk (5 years), 0.10 risk (10 years), 0.04 risk (25 years), 0.02 risk (50 years) and 0.01 risk (100 years) scale. The risk level is inversely related to the return period.

3 Methodologies for Climate Change Identification

Typically, methodologies take into consideration all of the available hydro-meteorological records for modeling and practical applications to manage any water resources as surface or groundwater storages. If the impact of climate change is not taken into consideration, such an approach may underestimate the magnitude of water-related quantities,

Fig. 4 PDFs for the Diyarbakir meteorological station for 1st half (top), 2nd half (middle) and total period (bottom)



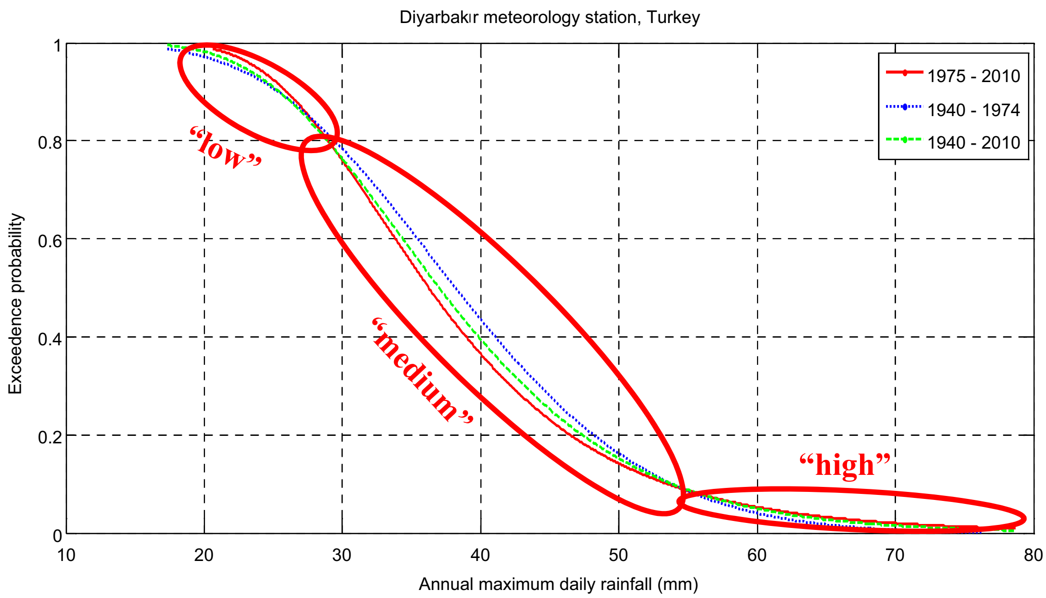


Fig. 5 The comparison PDFs for the Diyarbakır station

which may then lead to biased and possibly risky solutions. Şen (2012) and Mohorji et al. (2017) mentioned that the available hydro-meteorological records are divided into two halves. The first half is the older records and second half is the more recent records. Such an approach provides information about any change in the recorded behavior over time. A similar approach is taken for the global temperature records assessment by comparing cumulative probability distribution functions as shown in Fig. 1.

The climate change can be indicated from the difference between the two CDFs. According to Şen (2012) and Mohorji et al. (2017), the trend can be identified by sorting the data from the two halves in ascending order and then plotting them against each other on a scatter diagram. The innovative trend template (ITT) scatter graph is shown in Fig. 2. From the 1:1 (45˚) transect line; the upper triangular area indicates an increasing trend, while the lower triangular area indicates a decreasing trend. The procedures are based on daily maximum rainfall record from annual time series using the PDF, IDF and ITT analyses. Contrary to typical procedures, in this case, the available time series of rainfall records are divided into two halves, to assess the climate change effect based on historical records.

4 Study Area

There are two different regions, one in southeast Turkey and another in western Saudi Arabia taken into consideration to highlight how the climate change effect may be applied to water resource structural design procedures. Diyarbakir in southeast Turkey and Jeddah in western Saudi Arabia are shown Fig. 3. Climate type at Diyarbakır station is of continental climate type (dry and hot summers with cold and wet winters). Diyarbakir meteorological station is located in the Southeastern province of Turkey with Mediterranean type of climate interfered by some continental effects. Summer maximum temperatures may reach 45 °C with the minimum temperature drops from 15 to 20 °C. It is located in a semi-arid climate region. The Jeddah meteorological station along the Red Sea has different air mass movements. The winter climate is dominated by Mediterranean type climate extends to this Jeddah station location, whereas during the springtime, a monsoon air movement from the Indian sub-continent reaches to this station location (Almazroui et al. 2012).

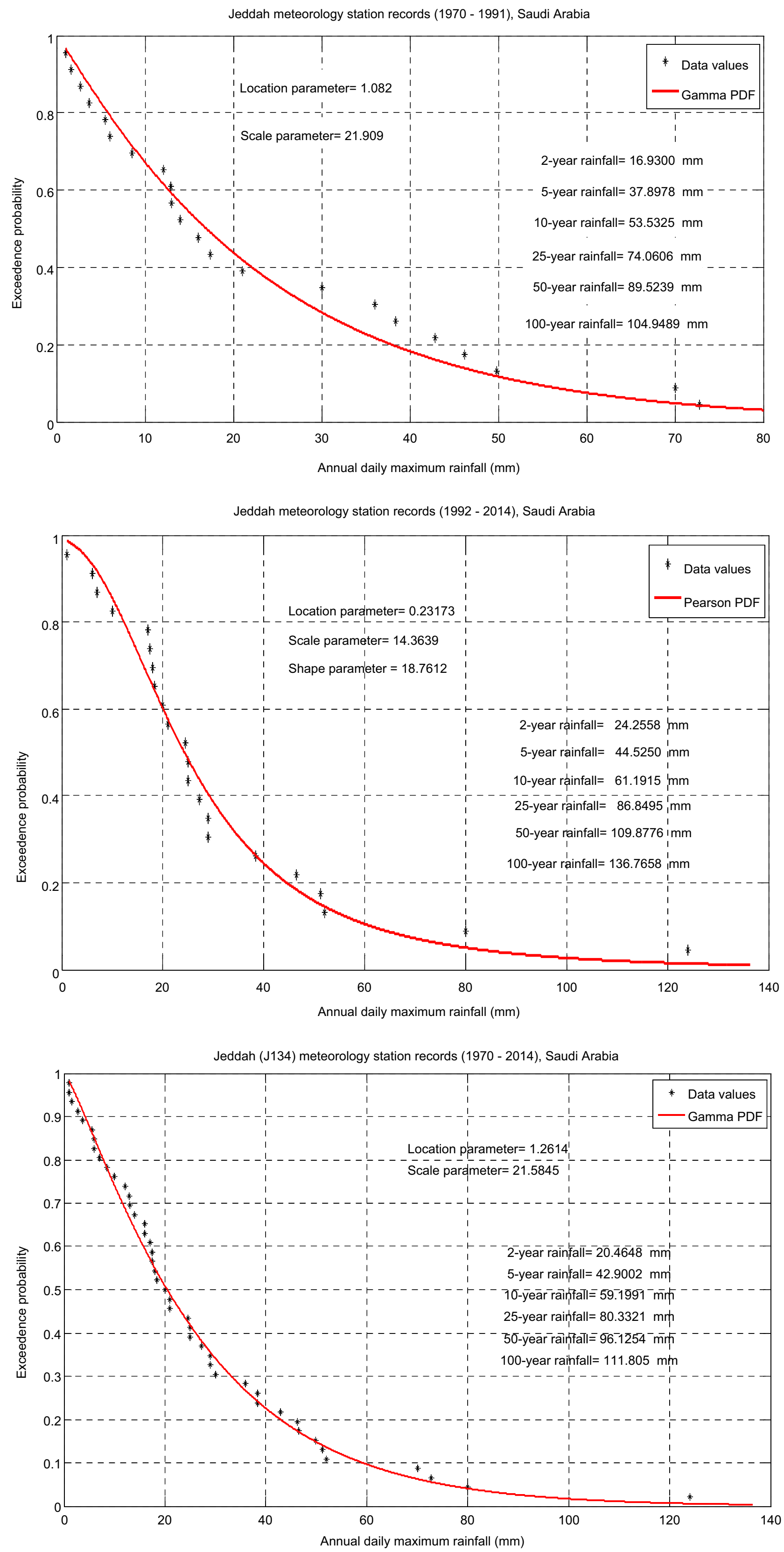
5 Applications

Application of the design procedures based on rainfall records are considered in three sub-sections. For both stations, annual daily maximum records are used. The data available at the Diyarbakır station are from 1940 to 2010, whereas the same type of data are available for the Jeddah station from 1970 to 2014, inclusive.

5.1 Cumulative PDF

The PDF of any hydro-meteorological record helps to conduct different probabilistic, statistical and stochastic studies and also the application of ITT method. Figure 4 shows the half record PDF with scale, location, and shape for Diyarbakir

Fig. 6 PDFs for the Jeddah meteorological station for 1st half (top), 2nd half (middle) and total period (bottom)



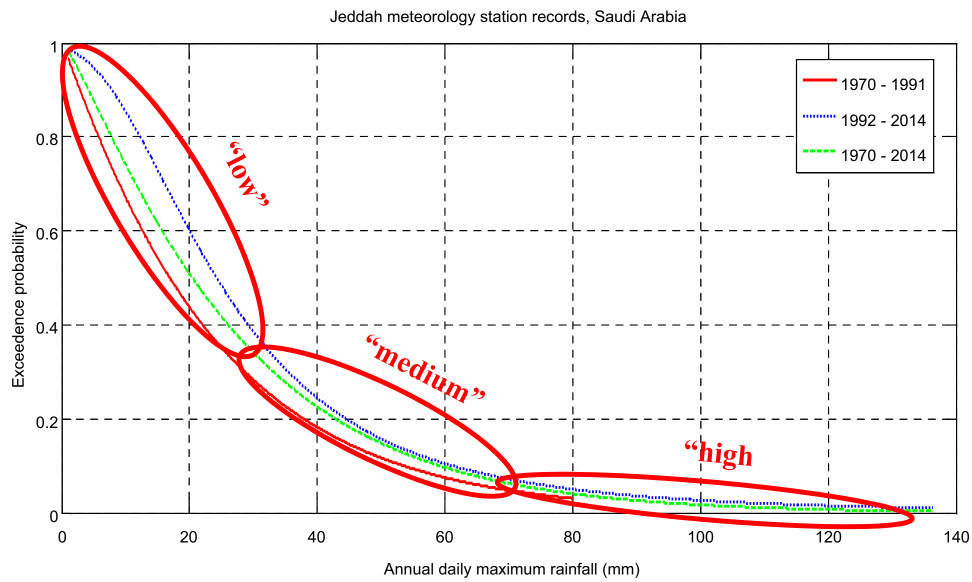


Fig. 7 The comparison PDFs for the Jeddah station

station. The rainfall amounts for the return periods 2 years, 5 years, 10 years, 25 years, 50 years and 100 years corresponding to the respective risk levels of 0.50, 0.20, 0.10, 0.04, 0.02 and 0.01 are also shown in the same figure. The increase of rainfall amount in the second half is clearly noticed.

Figure 5 provides the PDF comparisons. It can be seen that there are more "low" and "high" rainfall values during the second half (1975–2010), but fewer "medium" rainfall amounts compared to both the overall PDF record and the first half (1940–1974).

The Jeddah station PDFs are given in Fig. 6 for each half period. Increase of rainfall is noticed during the second half, especially for the values of "low" records. The comparison of PDF is shown in Fig. 7. The recorded values for the second half seem to be higher than for the first half, which is very obvious for "low" values range with a slowly decreasing rate for the "medium" and "high" ranges. It is recommended to use the second half values to water resources systems design and management since they will be more reflective of climate change.

5.2 IDF Curves

The most relevant information for any water resources system design are the intensity–duration–frequency (IDF) curves. By calculating the return period, by providing rainfall intensity they contribute to improved water structure design. The concentration time is out of the scope of the work (Şen 2008). The IDFs of Diabakir station for the two halves are shown in Fig. 8. It is obvious that rainfall intensity is higher during the first half period (1940–1974) than it was during the second half, and therefore, that rainfall intensity is on a decreasing trend in the Diyarbakır region. Figure 9 provides comparative information among the three cases for the 100-year and 2-year return periods with risk levels 0.01 and 0.50, respectively. In the graph, the rainfall intensity is highest within the first half period. The relative error, α, is the difference between the first half and whole period expressed as,

$$\alpha = 100 \times \frac{R_{max} - R_{min}}{R_{max}}, \quad (1)$$

where R_{max} and R_{min} represent as comparative values. For 100 years, the relative difference is 5.4%, while for 2 years it is 3.1%. It is recommended that the design variables for any water structure project in the future climate in this region to be augmented by 5% on average.

Figures 10 and 11 give the IDFs for the Jeddah station. The highest rainfall intensity is observed for the entire record periods, and therefore, the climate change implies an increasing trend in this region. On comparisons of the 100-year and 2-year IDF curves, an increase in the 2nd half is found with differences of 15.65% and 18.25%, respectively. The design values can be increased by 15% or 20% for any future water structure project, depending on the location of the project and at the discretion of the decision maker. Rainfall intensity for the return period and duration is provided in Tables 1 and 2.

5.3 ITT

In terms of climate change impact, the comparison of two halves ITT graphs is another important assessment of rainfall record (Sect. 3). The ITT curve of Diyarbakir station is shown in Fig. 12. The complete rainfall record trends are shown in this figure, which is in decreasing trend, and explicitly shown in Fig. 13. Taking into account the arithmetic averages of the first and the second half series to be

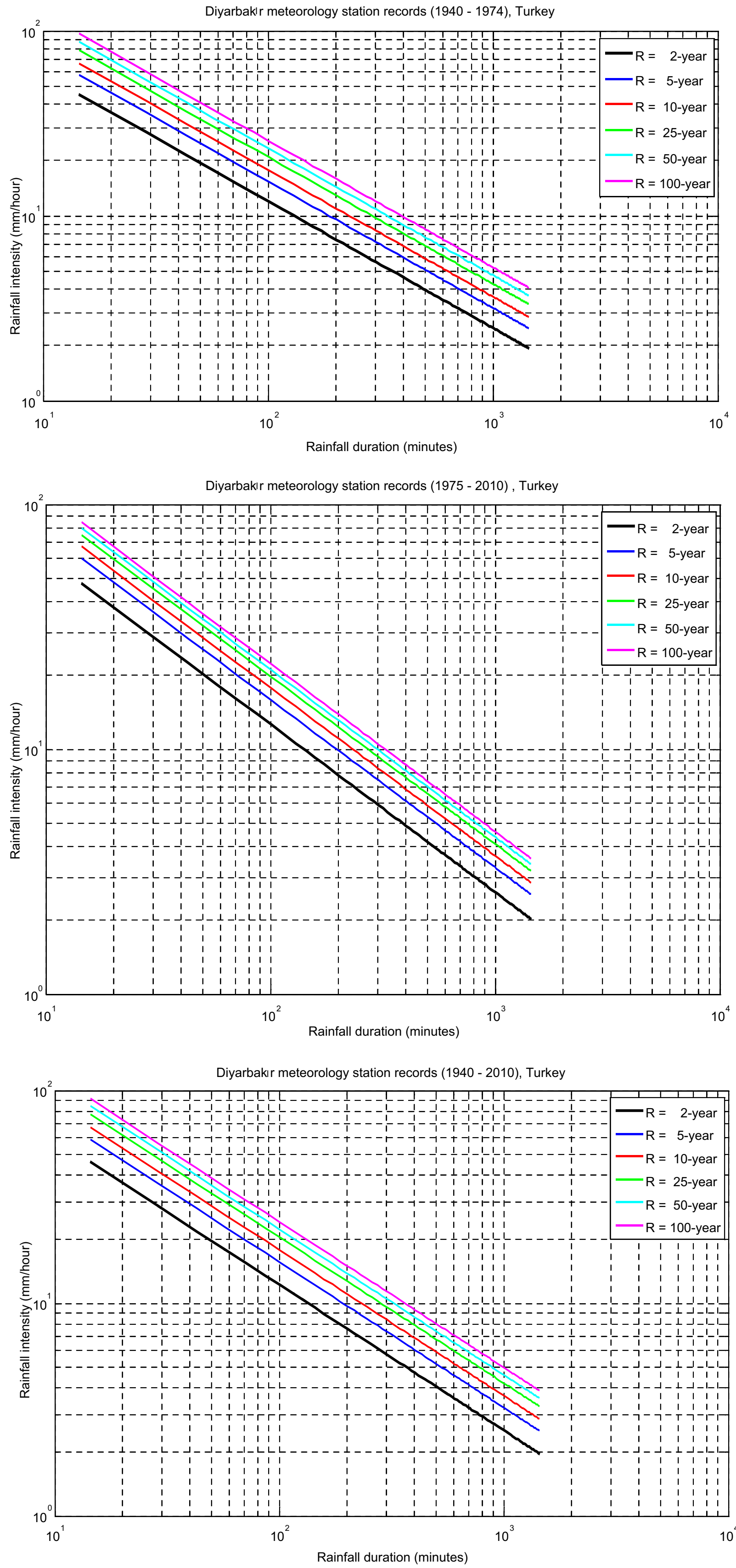


Fig. 8 IDF curves for the Diyarbakır meteorological station

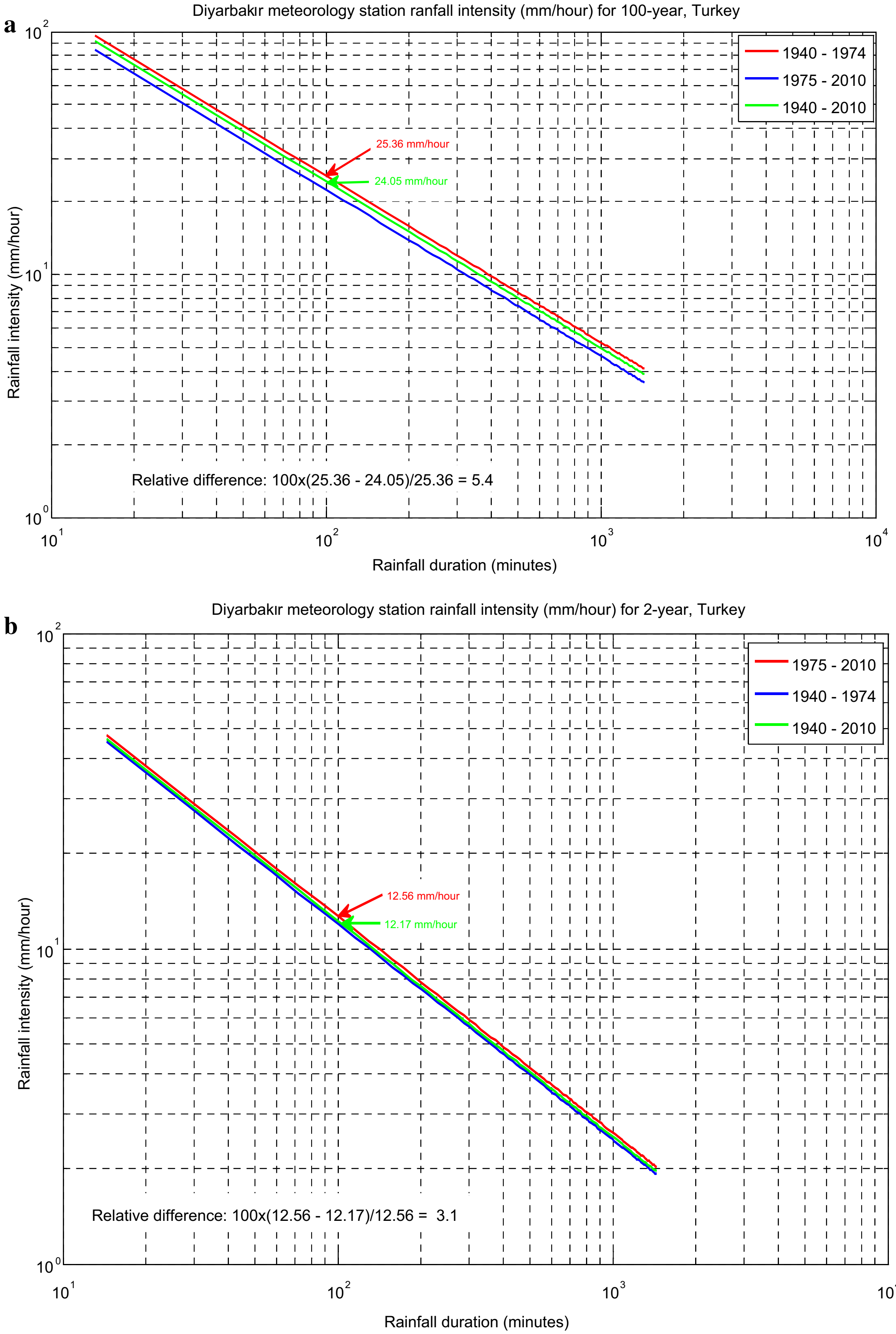


Fig. 9 The comparison of IDFs for the Diyarbakır station

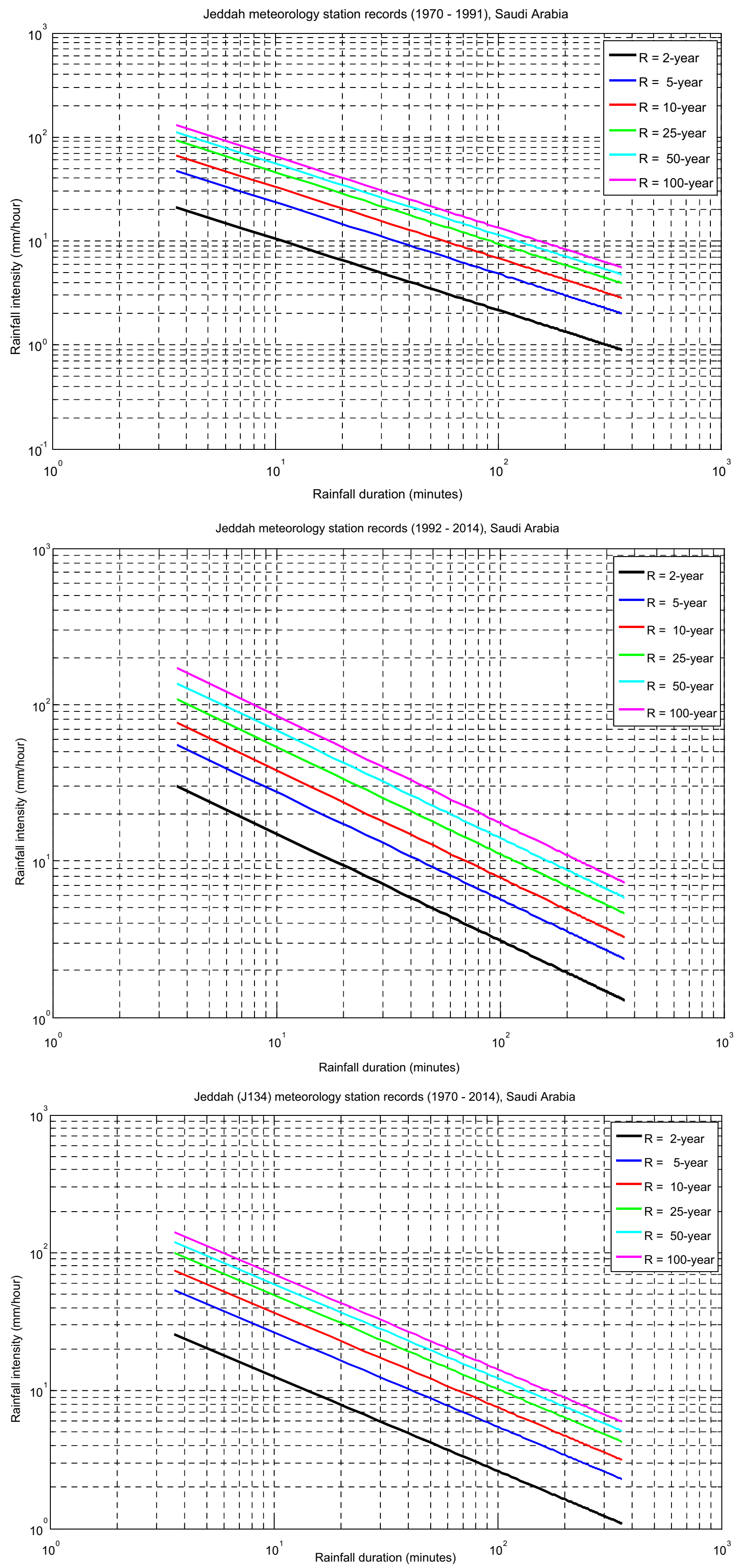


Fig. 10 IDF curves for the Jeddah meteorological station

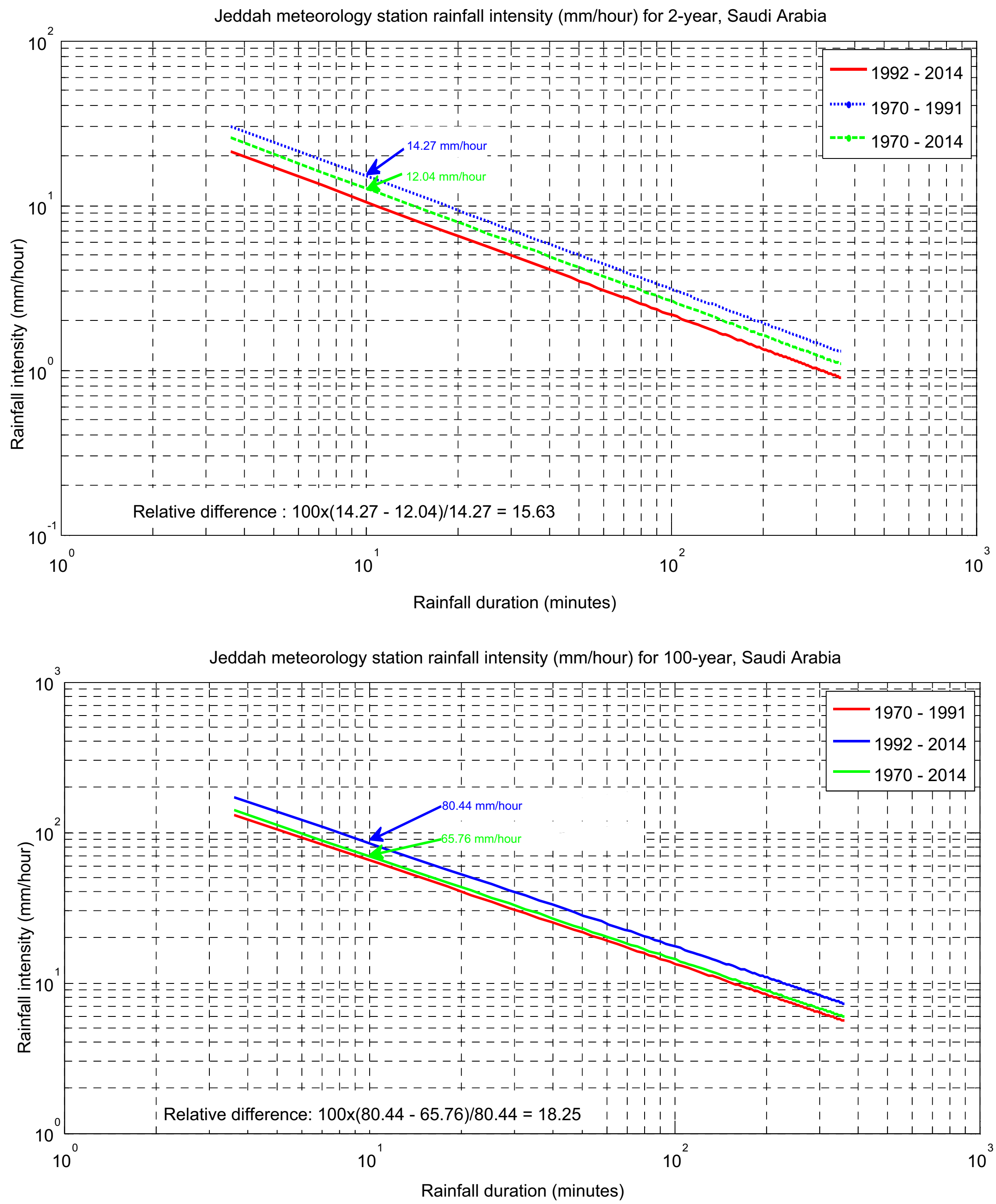


Fig. 11 The comparison of IDFs for the Jeddah station

$\bar{R}_1$ and $\bar{R}_2$, respectively, the slope, S, is calculated using the expression (Şen 2015),

$$S = \frac{2\left(\bar{R}_2 - \bar{R}_1\right)}{n}, \quad (2)$$

where n is the complete rainfall time series length.

The ITT methodology has its advantage, because it provides a visual inspection of different rainfall categories with possible trend component. Scrutiny of Fig. 12 shows a slightly positive trend at "low" ranges of rainfall, though some points are in upper side of the 1:1 line. However, in the range of "medium" rainfall, there is a negative; but "high"

Table 1 IDF values for the Diyarbakır meteorology station in Turkey

Return period (year)	Time series duration (year)	Rainfall duration (mm)						
		10	20	30	60	120	180	360
2	1940–1974	29.6524	15.8206	11.4623	7.1266	4.3383	3.2629	2.0286
	1975–2010	28.1553	15.0219	10.8836	6.7668	4.1193	3.0981	1.9262
	1940–2010	28.7354	15.3314	11.1079	6.9062	4.2042	3.162	1.9659
5	1940–1974	37.4037	19.9562	14.4586	8.9895	5.4724	4.1158	2.5589
	1975–2010	36.0868	19.2536	13.9496	8.673	5.2797	3.9709	2.4688
	1940–2010	36.7627	19.6142	14.2109	8.8354	5.3786	4.0453	2.5151
10	1940–1974	41.7916	22.2972	16.1548	10.044	6.1144	4.5986	2.8591
	1975–2010	41.5534	22.1702	16.0627	9.9868	6.0795	4.5724	2.8428
	1940–2010	41.8151	22.3098	16.1639	10.0497	6.1178	4.6012	2.8607
25	1940–1974	46.6108	24.8685	18.0177	11.2023	6.8195	5.1289	3.1888
	1975–2010	48.7158	25.9916	18.8314	11.7082	7.1274	5.3605	3.3328
	1940–2010	47.9702	25.5938	18.5432	11.529	7.0184	5.2785	3.2818
50	1940–1974	49.728	26.5316	19.2227	11.9514	7.2755	5.4719	3.4021
	1975–2010	54.2199	28.9282	20.9591	13.031	7.9327	5.9662	3.7094
	1940–2010	52.4202	27.968	20.2634	12.5985	7.6694	5.7682	3.5863
100	1940–1974	52.4834	28.0017	20.2878	12.6137	7.6787	5.7751	3.5906
	1975–2010	59.8493	31.9317	23.1352	14.384	8.7564	6.5856	4.0945
	1940–2010	56.7744	30.2911	21.9465	13.645	8.3065	6.2473	3.8842

Table 2 IDF values for the Jeddah (J134) meteorology station in Saudi Arabia

Return period (year)	Time series duration (year)	Rainfall duration (mm)						
		10	20	30	60	120	180	360
2	1970–1992	13.1493	7.0156	5.0829	3.1603	1.9238	1.4469	0.8996
	1992–2014	18.8391	10.0513	7.2824	4.5277	2.7563	2.0730	1.2889
	1970–2014	15.8946	8.4803	6.1442	3.8201	2.3255	1.7490	1.0874
5	1970–1992	29.4345	15.7044	11.3781	7.0742	4.3065	3.2389	2.0137
	1992–2014	34.5818	18.4506	13.3678	8.3113	5.0595	3.8053	2.3659
	1970–2014	33.3198	17.7773	12.88	8.008	4.8749	3.6664	2.2795
10	1970–1992	41.5778	22.1832	16.0722	9.9927	6.0831	4.5751	2.8445
	1992–2014	47.5264	25.357	18.3716	11.4223	6.9534	5.2297	3.2515
	1970–2014	45.9789	24.5314	17.7735	11.0504	6.727	5.0594	3.1456
25	1970–1992	57.5215	30.6897	22.2353	13.8245	8.4158	6.3295	3.9353
	1992–2014	67.4545	35.9893	26.075	16.2118	9.869	7.4225	4.6148
	1970–2014	62.3926	33.2886	24.1183	14.9952	9.1284	6.8655	4.2685
50	1970–1992	69.5317	37.0976	26.8779	16.711	10.1729	7.6511	4.7569
	1992–2014	85.3400	45.5319	32.9888	20.5103	12.4858	9.3906	5.8385
	1970–2014	74.6589	39.8331	28.8599	17.9433	10.9231	8.2152	5.1077
100	1970–1992	81.512	43.4895	31.509	19.5903	11.9257	8.9693	5.5766
	1992–2014	106.2236	56.674	41.0614	25.5294	15.5412	11.6885	7.2672
	1970–2014	86.837	46.3306	33.5674	20.8701	12.7048	9.5553	5.9409

range has a significantly increasing trend. The ITT graph for the Jeddah meteorology station is presented in Fig. 14 and the trend component of the complete series is presented in Fig. 15.

The complete series shows a significant increase trend (0.34) as shown in Fig. 14. However, detailed trend analysis of the ITT graph indicates that values for "low" are in increasing trend, while there is no significant trend detected

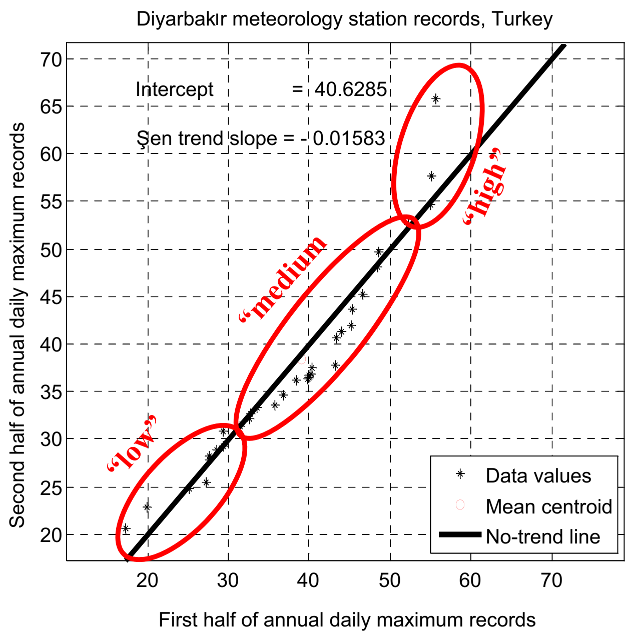


Fig. 12 IIT of the Diyarbakır meteorological station

for the "medium" rainfall values, the "high" rainfall range shows significant increasing trend because all points fall around 1:1 line. One can conclude from the trend component in Fig. 15 that all "low", "medium" and "high" ranges are average.

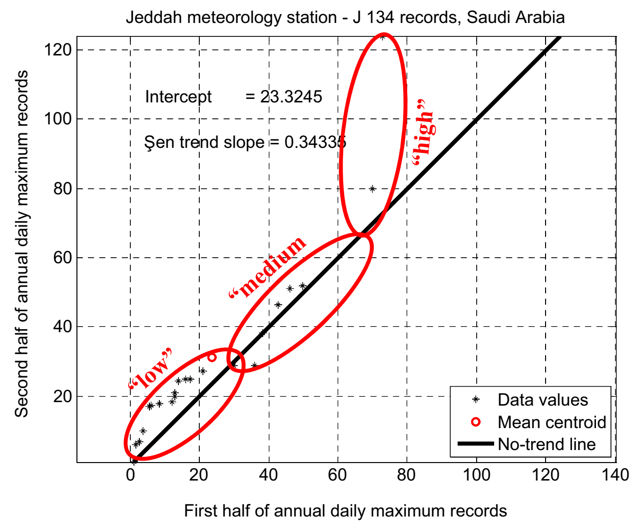
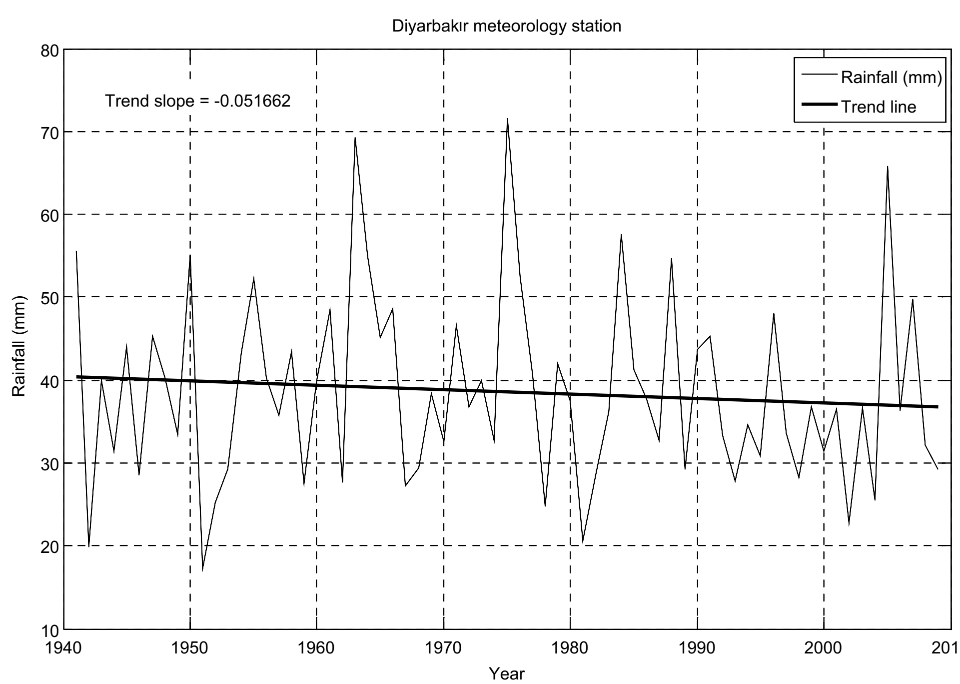


Fig. 14 ITT for the Jeddah meteorological station

6 Conclusions

It is well known that social, environmental, agriculture, health and some other sectors are affected by the climate change. Such an impact has not been investigated sufficiently for adaptation purposes for water resources system design. To clarify this point, three different methodologies are used: the PDF, IDF curves and ITT methods. Each methodology is applied to an annual daily rainfall time series from a semi-arid region represented by southeast Turkey and from an arid region represented by western Saudi Arabia. In addition to

Fig. 13 Rainfall trends for the Diyarbakır meteorological station



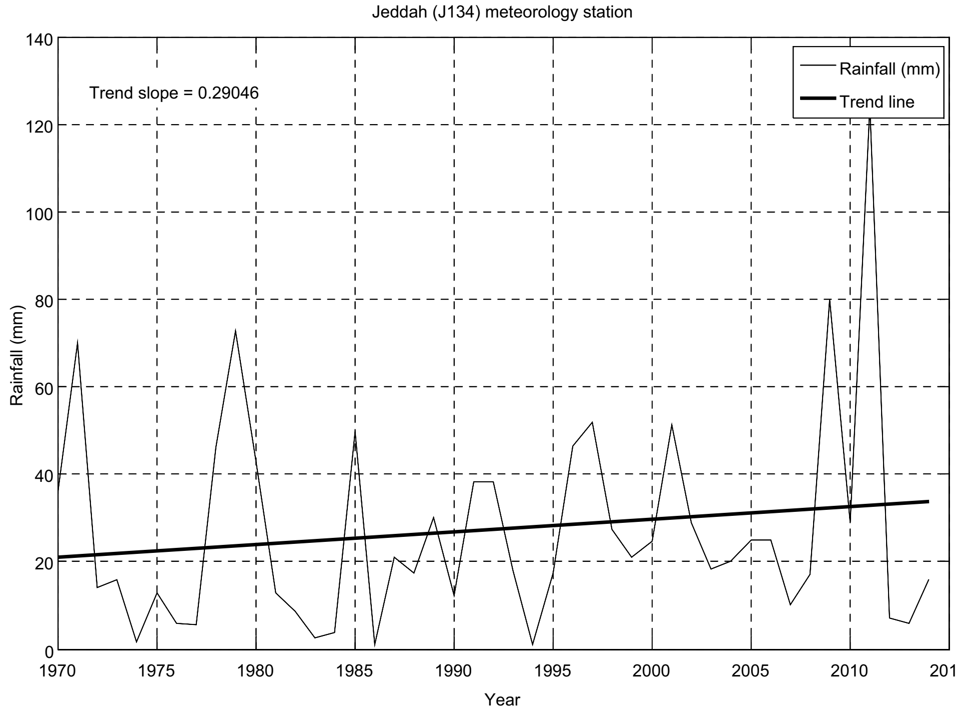


Fig. 15 Rainfall trends for the Jeddah meteorological station meteorology station

the typical analysis of the complete time series, the annual daily maximum rainfall time series are divided into half and analyzed in this paper. The second half of the time series is compared with the older half to determine any climate change impact from the historical records. The significant conclusions are that decision-making for future projects in the semi-arid region of Turkey should take into consideration an average increase of 5% in rainfall intensity, while the comparable figure for the arid region of Saudi Arabia is between 15 and 20%.

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