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Water resources and rainfall distribution function: a case study in Lebanon

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ABSTRACT

Rainfall and air temperature are major parameters of climate affecting changes in the environment. Rainfall is considered as the vital source of water around the world. In this paper, a detailed review has been conducted to highlight the main water resources in Lebanon. Furthermore, a statistical analysis of climate parameters including air temperature and rainfall amount in the Lebanese capital (Beirut) with different terrain conditions has been conducted. The climate data were collected from the meteorological service for a period of 25 years (1991–2015). The data were recorded over various periods to explore different climatic environments. The results showed that the mean air temperature and rainfall are within the ranges of 14.65°C to 17.98°C and 22.63 to 73.1 mm, respectively, during the investigation period. In addition, four distribution functions have been used to analyze the precipitation characteristics at the studied stations. Based on the results, it was observed that the Gumbel Maximum and Logistic distributions were able to provide the best fit to the actual data for the locations studied.

Keywords: Air temperature; Beirut; Distribution functions; Lebanon; Rainfall; Water resources

1. Introduction

Water availability and use depend on several factors including increased population, energy demand, and related environmental problems [1,2]. Climate change significantly affects the environment and natural resources [2]. Air temperature and precipitation (rainfall or snow) are the major parameters of climate that influence human activities such as urban water resources [3] and agricultural production [4,5]. Precipitation is one of the most important factors in the Earth's water cycle, affecting a number of human activities, such as agriculture, with significant impacts in the economy [6,7].

No theoretical distribution can be considered that can exclusively characterize the annual rainfall profile [8]. Thus, the analysis of precipitation data is mainly based on its distribution type. Many researchers have studied the precipitation (rainfall) characteristics using different distribution functions in different parts of the world. For instance, Sen and Eljadid [9] used a Gamma distribution function to investigate the rainfall characteristics for 29 stations in Libya based on data from the previous 20 years. Michaelides et al [8] studied the characteristics of the annual rainfall frequency distribution in Cyprus using a Gamma distribution function. Hanson and Vogel [10] analyzed the daily rainfall characteristics across the United States using different distribution functions. They concluded that three-parameter Pearson-III distribution and four-parameter Kappa distribution can be considered as the best distribution functions to study full record daily rainfall and wet-day precipitation amount data. Khudri and Sadia [11] determined the best-fit probability distribution of annual maximum rainfall data of 22 stations in Bangladesh by using seven distribution functions. They found that generalized extreme value and four parameters generalized gamma distribution were able to provide a good approximation of the observed rainfall data in each station. Mohamed and Ibrahim [12] used five distribution functions to analyze the rainfall data in Sudan. It was found that normal and Gamma distribution were the best-fit probability distributions for the annual rainfall during the period of the study.

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Lebanon is a small Mediterranean country (surface area 10,452 km^2, and average width 45 km) located in South-West Asia, between N latitude 34°42′ and 33°3′and E longitudes 35°6′ and 36°37′ [13]. Lebanon's physiography is unique, dominated by two mountain ranges which run parallel to the sea (NNE-SSW) and are separated by the Bekaa valley. Lebanon has mild, dry summers and cold, wet winters. The heaviest rainfall occurs between November and April, with relatively minimal precipitation, if any, between July and August [14]. Lebanon is a Middle Eastern country that is fortunate to have significant water resources, unlike its neighbors. However, rain is mainly concentrated in the winter months. While water is abundant in winter, significant water shortages are still experienced around the country for the rest of the year. In addition, water quality in many areas is questionable.

The review, therefore, seeks to assess water resources with a focus on drinking water and the quality of water in terms of physicochemical parameters in the dry season as well as to highlight the importance of adopting a water demand strategy using different scenarios made by the Ministry of Environment of Lebanon. Moreover, the present study aims to analyze the characteristics of rainfall in the most populated region (Beirut) in Lebanon using non-parametric statistical distributions. This was performed on the average monthly precipitation data to show transitions in wet to dry and dry to wet among three different non-overlapping climate periods of 25 years each, that is, 1991–2000, 2001–2010, and 2011–2015. This enables the observation of an increase or decrease in rainfall received in each of the climatic zones of the Beirut region.

2. State of water resources in Lebanon

Lebanon's water resources are classified into groundwater and surface water. The sources of surface water resources in Lebanon are from 16 river systems, as shown in Fig. 1.

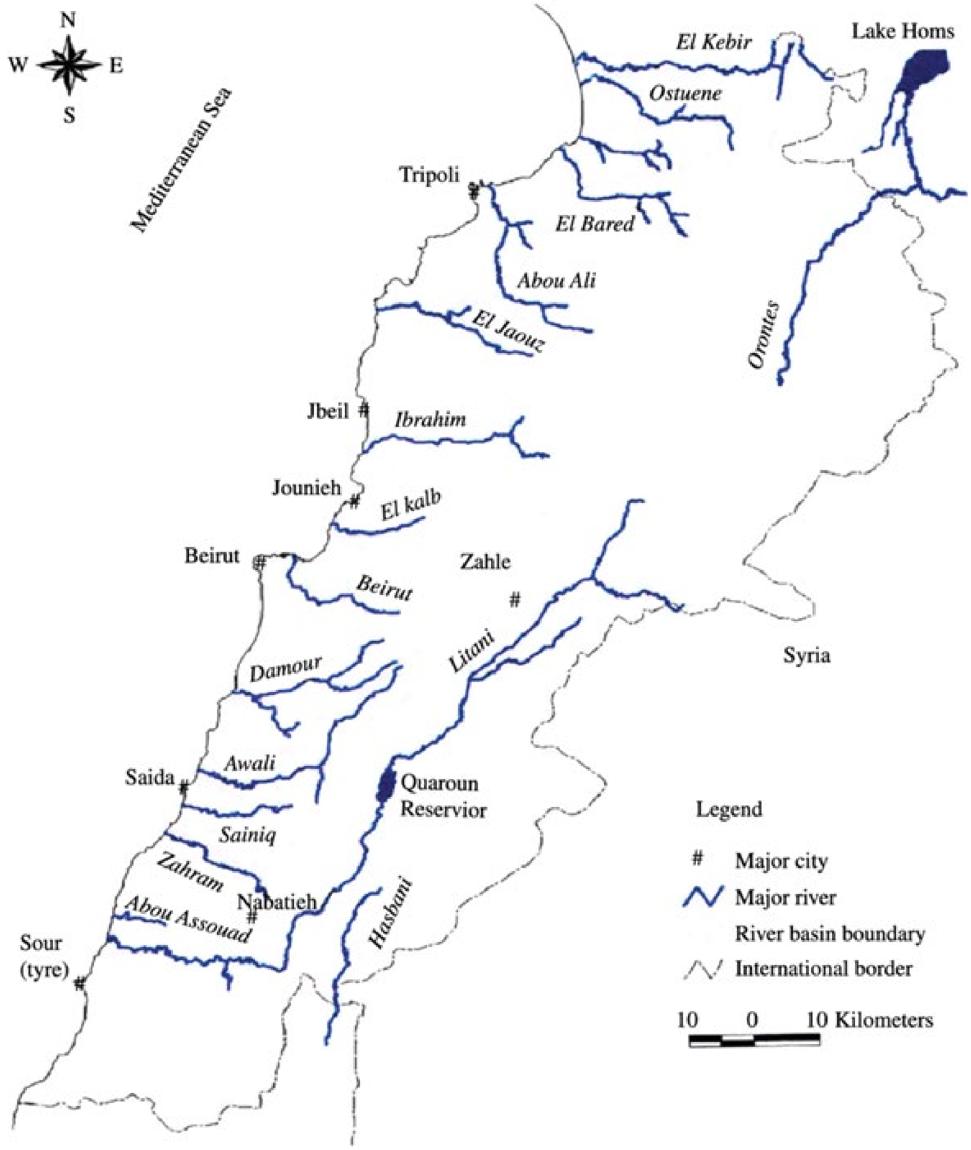

Fig. 1. 16 perennial rivers of Lebanon.

The main water resources in Lebanon are groundwater (51%), and surface water (49%), as shown in Fig. 2. In general, surface water resources are principally sourced from rivers (46%) and surface storage such as dams and lakes (3%) [15].

2.1. Surface water resources in Lebanon

Lebanon has 40 rivers, 16 of which are permanent (Fig. 1). The combined annual flow of rivers is estimated to be about 3,900 million m^3, where the majority of the flow (75%) occurs between January and May [16]. Surface water resources are mainly sourced from 16 river main-stream discharges in Lebanon, particularly: El Kabir, Ostuene, El Bared, Abou Ali, El Kjaouz, Ibrahim, El Kalb, Beirut, Damour, El Awali, El Zahrani, El Assi, Al Qasmieh, Litani, Wazzani and Hasbani (Fig. 1). The Kusba and Abu Samra comprise the Abou Ali river systems. Al-Janin and Al Khodaira constitute the Ibrahim river systems. In addition, El Yamouneh, Qaraoun heights, Qaraoun El Khardali and El Khardali Sea form the Litani river systems. Table 1 presents the short time-series discharge data from 1971 to 1975 and from 2005 to 2009 for the 16 perennial rivers in Lebanon. According to the State of the Environment Report of Lebanon, El Assi and Hasbani are the only two rivers that do not discharge into the Mediterranean Sea. Additionally, the highest river flows in Lebanon are associated with Nahr el Litani, Nahr Ibrahim, and Nahr el Assi. Rivers are mainly replenished from springs that are fed from melting snow. Over 2,000 regular springs feed into different streams in Lebanon, creating an aggregate of 1,150–1,200 Mcm/year of water that is not completely misused [17]. Most of the surface water resources come from springs, where 637 Mcm/

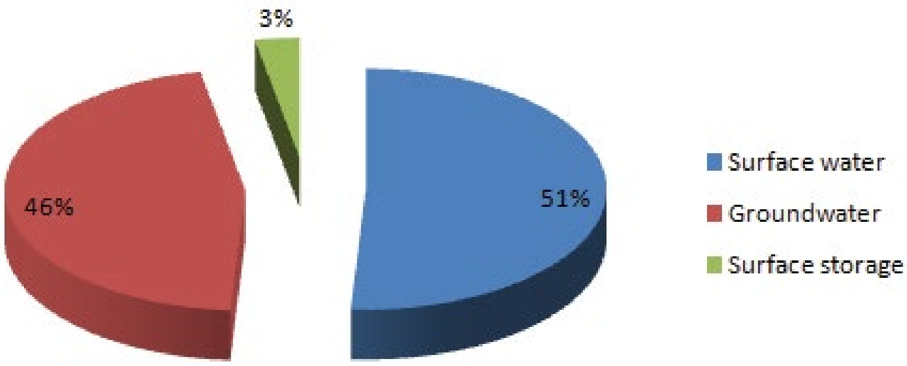

Fig. 2. Water resources in Lebanon.

Table 1
Flow data for the 16 perennial rivers of Lebanon (1971–1975 and 2005–2009) [19]

River name	River length (km)	Annual average volume		Average flow		Maximum flow		Minimum flow	
		(71–75) Mm^3	(05–09) Mm^3	(71–75) m^3/s	(05–09) m^3/s	(71–75) m^3/s	(05–09) m^3/s	(71–75) m^3/s	(05–09) m^3/s
El Kabir	58	259.2	283.9	9.1	91.3	48.5	190.8	1.5	1.4
Ostuene	44	–	47.0	–	1.6	–	6.9	–	0.0
El Bared	24	132.8	120.1	4.2	3.8	24.0	18.9	0.2	0.5
Abou Ali	45	148.6	206.6	4.6	6.6	25.2	32.5	0.6	1.1
El Kjaouz	38	32.3	44.6	1.0	1.4	11.4	17.9	0.0	0.0
Ibrahim	30	208.6	329.2	6.6	10.5	65.5	79.1	0.1	0.3
EL Kalb	38	154.1	189.3	4.9	6.1	29.3	67.0	0.2	0.0
Beirut	42	47.9	81.8	1.5	2.6	25.1	49.9	0.0	0.0
Damour	38	–	166.9	–	5.4	–	51.0	–	0.1
EL Awali	48	393.7	252.9	12.5	8.1	51.7	32.2	1.9	1.6
El Zahrani	25	19.2	17.5	0.6	0.6	10.6	4.5	0.0	0.0
El Assi	46	326.4	275.5	11.0	8.7	13.8	12.4	8.8	6.0
Al Qasmieh	–	151.7	131.3	4.8	4.2	47.6	46.6	0.8	0.0
Litani	170	–	167.8	–	5.4	–	43.6	–	0.0
Wazzani	–	–	71.9	–	2.3	–	19.5	–	0.5
Hasbani	21	38.4	28.7	1.2	0.9	9.9	14.9	0.0	0.0

year is currently used [18]. The surface water supply also comes from storage dams, namely the Qaraoun dam and the Chabrouh Dam, which currently provide about 45 Mcm/year of water [18].

2.2. Groundwater resources in Lebanon

Almost half of Lebanon's water supply comes from groundwater. The main aquifers in Lebanon are limestone and are characterized by their karstic nature, meaning that rainwater and melting snow (the main sources of groundwater recharge) are quickly infiltrated underground, feeding deep underground aquifers containing a huge number of sewers [20]. In addition, the Keserwan Limestone Formation and the Sannine-Maamelte in Limestone Formations, which are known as the first and second water towers of Lebanon, are the two major aquifer systems in the country [21]. There are also additional aquifers of local importance [22,23]. The natural recharge rate of groundwater basins is estimated at 500 Mcm/year, but with an extraction rate of around 700 Mcm/year, over-exploitation is a growing problem, especially in Beirut, Tripoli, South Lebanon, and Bekaa. Coastal aquifers are also particularly affected and increasingly suffer from groundwater degradation and seawater intrusion [24–26].

2.3. Water quality

Water resources in Lebanon are heavily polluted, as domestic and industrial wastewater is largely untreated, and intolerable agricultural practices exacerbate the situation. The main rivers in Lebanon have very high levels of bacterial contamination due to the flow of raw sewage, which poses a real threat to public health [27,28].

Random disposal of solid waste also results in water contamination due to leakage of chemicals. In addition, chemical contamination of surface and groundwater from industrial discharges is also common. Untreated wastewater containing heavy metals is often poured away [29], while leaks of underground gasoline tanks and uncontrolled pumping of oil and petroleum by-products are also common.

Coastal waters in Lebanon are also heavily polluted by wastewater flowing from domestic sewage discharges, industrial wastewater discharges, coastal agricultural waste, and huge waste dumps on the waterfront (in Tripoli, Bourj Hammoud, Beirut, Saida, and Tire). Oil spills (especially the large leakages that occurred after the 2006 war with Israel), and coastal power stations (in Beddawi, Zouk, Jiyeh, and al-Zahrani) are other sources of pollution. Several studies on the coastal and marine waters in Lebanon have found very high levels of pollutants, particularly in areas close to the three main cities of Tripoli, Beirut, and Sidon, including heavy metals, which are toxic to both marine and human populations [30–32].

The intensive use of fertilizers and pesticides in agricultural practices, especially during the dry seasons, has led to the filtration of nitrates into the soil and the contamination of groundwater systems with high concentrations found in coastal plains [33,34] and the Bekaa Valley [35]. As farmers rely on wells for irrigation, health and environmental concerns are increasing. In addition, it is reported that raw sewage is used for irrigation in many areas, including Akkar and Bekaa [36], and farmers throughout the country are likely to resort to this practice when freshwater is not available [37].

Table 2 summarizes the parameters for selected rivers in the dry season. In the dry season, the highest average TDS (total dissolved solids) was found in the Antelias river (300 mg/L) and the lowest was found in the Ibrahim river (150 mg/L). In addition, the lowest average BOD (biological oxygen demand) was found in the Kabir river (14 mg/L), whereas the highest average value was found in the Ibrahim river (63 mg/L).

Total coliform (TC) and *Escherichia coli* tests are the most significant tests used to identify the water quality [38,39]. Total coliforms are a group commonly found in the environment. *Escherichia coli* is the only member of the total coliform group, which are bacteria that are found mainly in the intestines of mammals including humans [40–42]. Microbial contamination is mildly infectious and causes invisible pollution of water, which leads to very serious issues. Each person discharges 100–400 billion coliforms per day in addition to another kind of bacteria [43,44]. Coliforms are harmless to man [40,45]. The presence of *E. coli* in water indicates recent fecal contamination and it may show the possible presence of disease-causing pathogens such as bacteria, virus, parasites, etc. [46–49].

Table 2
Physicochemical parameters for selected rivers in the dry season

River	BOD (mg/L)	NO_3 (mg/L)	TDS (mg/L)	SO_3 (mg/L)	Total coliform (c/100 mL)	*Escherichia coli* (c/100 mL)
Kabir	14	3	270	20	900	20
Bared	28	2.8	225	28	610	17
Abou Ali	39	3.4	280	22	26,500	3,000
Ibrahim	63	1	150	8	3,500	200
Antelias	53	3	300	30	28,000	6,000
Damour	21	3	200	38	490	15
Awali	33	7	210	22	710	1
Qasmieh	23	5.5	250	21	80	0

Source: Ministry of Environment Lebanon.

Therefore, Table 2 shows the variations in total coliform and *E. coli* for the selected rivers in Lebanon during the dry season. It is noticed that rivers show high values of TC and *E. coli*. The presence of TC and *E. coli* in the river water ranges from 80 c/100 mL to 28,000 c/100 mL and 0 c/100 mL to 6,000 c/100 mL, respectively. The pollution caused by the presence of fecal coliform bacteria is related to human activity [40,50,51]. This may cause gastrointestinal illness, fever, diarrhea and dehydration. High value of TC and *E. coli* is observed in the Abou Ali and Antelias rivers. This indicates that domestic pollution exists in the river due to the presence of *E. coli*.

In the Litani River Basin, for example, water resources are heavily polluted. As shown in Tables 3 and 4, the mean pH values of surface water, lake water and groundwater of the Litani River Basin wherein the range of 7.93 to 8.72 unit in 2010. Compared with the drinking water standard limits, the pH values for surface and lake water were within normal limits (6.5–8.5). Furthermore, it is noticed that during the period (2005–2010), pH values increased by 11.84% for the water surface, 18.14% for lake water and 12.46 for groundwater in the upper part of the Litani River Basin. Thus, it is an important observation that the pH of the Litani River Basin has gradually increased over the years, which indicates that there is alkaline water impoundment affected by the surrounding C4 (Sannine limestone) formation [52]. Furthermore, it is observed that in 2010, the TDS value for the surface water of the Litani River Basin was 500 mg/L higher compared with the lake water (Table 3), which indicates that this water is unacceptable for human consumption as well as for irrigation purposes. According to Saadeh et al. [52], of the increasing population and the runoff from all other tributaries including the heavily polluted Berdawni led to the increase in the TDS value.

Untreated wastewater from towns and cities, large-scale dumping of waste, industrial wastewater disposal and

Table 3
Litani River Basin water quality

Indicator	BAMAS 2005 (summer)			LRBMS 2010 (summer)			Drinking water Standard	
	Min.	Mean	Max.	Min.	Mean	Max.	LIB-NOR	EPA
Surface water								
TDS (mg/L)	88	290.96	706	187	502	1,979	<500	<500
pH	6.57	7.09	7.68	7.27	7.93	8.66	6.5–8.5	6.5–8.5
BOD (mg/L)	2	48.46	624	2.50	547	2,530	NA	NA
Nitrates (mg/L as N)	3	13.46	62	0.10	1.23	4.90	45*	<10
Phosphates (mg/L)	0	11.75	197	0	8.58	72	NA	NA
Fecal coliform (CFU/100 mL)	0	223,487	1,500,000	1	71.61	400	0	0
Cadmium (mg/L)	NA	NA	NA	0.005	0.01	0.079		<0.005
Lake water								
TDS (mg/L)	120	160	196	221	235	256	<500	<500
pH	6.5	7	7.5	8.2	8.27	8.32	6.5–8.5	6.5–8.5
BOD (mg/L)	<2	2.57	4	2	2.65	3.30	NA	NA
Nitrates (mg/L as N)	16	21	62	0.8	0.93	1.2	45*	<10
Phosphates (mg/L)	0.01	0.13	0.35	0	0.09	0.24	NA	NA
Fecal coliform (CFU/100 mL)	0	17	450	0	160	400	0	0
Cadmium (mg/L)	NA	NA	NA	0.0007	0.01	0.021		<0.005

Source: Ministry of Environment Lebanon.

Table 4
Groundwater analysis in the upper Litani River Basin (2005 and 2010)

Indicator	BAMAS 2005 (summer)			LRBMS 2010 (summer)			Drinking-Water Standard	
	Min.	Mean	Max.	Min.	Mean	Max.	LIB-NOR	EPA
TDS (mg/L)	NA	NA	NA	170	385	863	<500	<500
pH	6.54	6.9	7.22	6.98	7.76	8.72	6.5–8.5	6.5–8.5
Nitrates (mg/L as N)	3	48	171	0.2	6.7	41	45	<10
Phosphates (mg/L)	0	0.3	12	0.1	1.2	6.43	NA	NA
Fecal coliform (CFU/100 mL)	0	42.8	400	0	39.2	400	0	0

Source: Ministry of Environment Lebanon.

uncontrolled agricultural disturbance (including fertilizers and pesticides used in the Bekaa Valley) not only severely affect the quality of water in rivers and streams but also contaminate groundwater [53].

In many places, water is also contaminated with heavy metals [54]. For instance, according to Wazne and Korfali [55], Canal 900 (Canal 900 is an open irrigation canal that acquires its water from Qaraoun Lake, which delivers 30 Mcm/year from Qaraoun Lake to the Litani River to irrigate the agricultural lands of the Bekaa Valley) has been plagued with setbacks due to excessive algal proliferation. Also, the level of nutrients in the surface water of this canal is high.

The excessive and uncontrolled pumping of groundwater, especially during the summer, has caused a sharp decline in the level of groundwater, which in turn has led to the leakage of seawater into groundwater along the coast, particularly in the Jiyeh and Damur areas. When groundwater becomes salty, the quality of drinking water is directly affected in some areas in and around Beirut, which makes it salty and unfit for consumption. They also suffer from agricultural water supplies, and this particularly affects farmers who rely on groundwater as their main source of water [24–26]. In addition, the high level of groundwater salinity can significantly affect the foundations of buildings [56].

2.4. Water demand in Lebanon

Water consumption is characterized by various types of demand, including domestic, industrial, irrigation and so on [57], which is related to the average income per capita and water consumption increases with the increase in income. Two scenarios have been designed to estimate the water demand in various sectors in Lebanon [20]. The first was carried out assuming that the annual population and irrigated areas are increased by 2.5% and 36% in 2030, respectively. In the second scenario, water consumption is 180 L/d for urban and 160 L/d for rural. Furthermore, it is assumed that the annual population and irrigated areas are increased by 1.75% and 67% in 2035, respectively. Table 5 shows the demand scenario for the Beirut area. According to Ministry of Environment [20], the annual water demand and the total share in three main sectors (domestic, industrial, and irrigation) are shown in Table 6. In addition, the water requirements in Lebanon until 2035 are presented. It can be observed that total annual water demand for domestic purposes will be increased by 44% in 2030, while the total annual water demand for irrigation purposes will be decreased by 18% in 2030 compared with 2010. Furthermore, it is found that the total water demand for various sectors in terms of domestic, industrial, tourism, and irrigation will be increased by 22% in 2035, that is, the total water demand in 2010 was about 1,473 mm^3, while in 2035, it would be around 1,802 mm^3, as shown in Table 6.

2.5. Water rationing

In 2000, the Department of Energy and Water published a 10-year water and wastewater management plan based on the principles of IWRM. Thus, it formed the basis for the National Water Sector Strategy for 2010 (NWSS), adopted by the Council of Ministers in 2012. The National Water Sector Strategy is designed to ensure "water supply, irrigation, and sanitation services throughout Lebanon on an ongoing basis and with optimal service, Environmental and economic and social" [20]. It outlines a series of infrastructure, technical and institutional measures that must be applied in the sector, and includes plans to conserve water, reduce waste rates, and adopt modern irrigation techniques. However, political and budgetary delays have slowed the implementation of the national water sector strategy, and so far, efforts have focused mainly on increasing water supply.

To encourage local users to reduce their water consumption during a severe drought in the summer of 2014, the Department of Energy and Water launched several public awareness campaigns. However, these campaigns only achieved limited success, as the drought period coincided with the already severe water shortage. Moreover, as users pay a uniform price for water consumption, and there are no measures to punish the wasteful use of water, there is little incentive to rationalize water consumption.

In addition to government efforts to rationalize water consumption, there have also been small-scale donor-funded initiatives to rationalize and reuse water, such as the reuse of gray water and rainwater harvesting. While such projects remain largely dispersed, they have stimulated communities and donors and can serve as a catalyst for further developments in this area [58].

3. Methodology

As mentioned previously (Section 2.4), the domestic water demand in different sectors for the capital area (Beirut) in Lebanon was estimated based on two scenarios.

Table 5
Low demand scenario for the Beirut area

Year	Population	Domestic consumption (m^3/d)	Non domestic consumption (m^3/d)	Total domestic consumption (m^3/d)	Unaccounted for water		Total demand
					% Total	m^3/d	m^3/d
2010	1,700,000	255,000	76,500	331,500	30	99,450	430,950
2015	1,787,161	268,074	80,422	348,496	25	87,124	435,620
2020	1,878,791	281,819	84,546	366,364	20	73,273	439,637
2025	1,975,118	296,268	88,880	385,148	20	77,030	462,178
2030	2,076,385	311,458	93,437	404,895	20	80,979	485,874

Table 6
Annual water demand in Lebanon

Sector	Annual water demand mm^3 and share of total					
	2010	%	2020	%	2030	%
Domestic	467	31	767	37	1,258	44
Industrial	163	11	268	13	440	16
Irrigation	900	58	1,020	50	1,120	40
Sector	Annual water demand in mm^3 by sector					
	2010	2015	2020	2025	2030	2035
Domestic	505	460	427	467	512	562
Industrial	152	138	128	140	154	169
Tourism	6	8	10	13	16	21
Irrigation	810	877	935	983	1,021	1,050
Sector	Annual water demand in mm^3 by water establishment					
	2010	2015	2020	2025	2030	2035
Beirut and Mount-Lebanon	373	373	374	407	443	482
North Lebanon	351	354	358	381	403	424
South Lebanon	256	242	234	251	268	285
Bekaa	493	513	533	563	589	612

Source: Ministry of Environment Lebanon.

In addition, climate change affects water resources through changes in temperature, rainfall, runoff and groundwater recharge. Furthermore, the changes in air temperature and rainfall could affect river flows, and hence, the mobility and dilution of contaminants [59]. Consequently, this study investigates the characteristics of the rainfall and air temperature in the capital city (Beirut) from 1991to 2015 (25 years). In this section, the statistical analysis of air temperature and rainfall in Beirut is discussed.

3.1. Study area and measurement data

This study was conducted in the Beirut region in Lebanon (Fig. 3). Beirut is the capital and largest city of Lebanon. Beirut is considered one of the most highly populated regions in Lebanon with a total population of about 1,916,100 people. Beirut is geographically located at latitude – 33° 53′ 19.0680″ N, longitude – 35° 29′ 43.7280″ E. The elevation from the sea level is about 100 m for the selected region. In the present study, monthly time series data of average temperatures and rainfall for the period (1991–2015) were used.

3.2. Rainfall analysis using statistics

Knowledge of time series precipitation data is required for water resource assessment. Several distribution functions are given in the literature to present rainfall data for the selected stations. In this work, 10 distribution functions are used to analyze the rainfall characteristics at the selected stations, as shown in Table 7. Furthermore, the Maximum likelihood method is used to estimate the parameters of the distribution functions.

4. Results and discussion

4.1. Description of rainfall data

Table 8 presents the descriptive statistics of time series data of precipitation including mean rainfall, standard deviation, variance, the coefficient of variation, minimum, maximum, Skewness and Kurtosis. It is observed that the monthly mean rainfall amount varies from 22.63 to 73.1 mm. Mean rainfall amount and standard deviation values suggest that there is good consistency in the rainfall behavior. The coefficients of variation are moderately high. During the investigation period, the Skewness values are positive, indicating that all distributions are right-skewed. The kurtosis values are moderately high, ranging from –1.59 to 5.27.

Variations in the monthly rainfall for three different periods in Beirut are illustrated in Fig. 4. From 1991 to 2001, the maximum monthly rainfall was recorded in February 1992 with a value of 228.6 mm followed by 225.83 mm in January 2001, as shown in Fig. 4. Also, during 2001–2010, the highest monthly rainfall was obtained in February 2003 with a value of 265.717 mm. Additionally, the highest value of monthly rainfall was recorded in 2012 for the period between 2011 and 2015. Moreover, it is found that the highest annual rainfall value was recorded in February 2003, while the lowest was obtained in the summer season during the investigation period. As shown in Fig. 5, the first and second peaks were in January and December, respectively. A comparison between the monthly rainfalls that occurred in each climatic period across Beirut shows a reduction in all months except in January, April, September and December, when there was a slight increase in the third climatic period (2011–2015) as

Fig. 3. Map showing the location of the studied region.

shown in Fig. 5. Moreover, Fig. 6 shows the annual rainfall during the investigation period (1991–2015).

4.2. Description of averaged temperature data

Table 9 presents the descriptive statistics of the temperature including mean, standard deviation, variance, the coefficient of variation, minimum, maximum, Skewness, and Kurtosis. During the investigation period, the mean averaged temperature varied from 14.65°C to 17.98°C. The mean temperature and standard deviation values suggest that there is good consistency in temperature behavior. The coefficients of variation depending on the year, that is, a positive value indicates that all distributions are right-skewed, while a negative value of Skewness indicates that all distributions are left-skewed.

Fig. 7 illustrates the monthly mean temperature at the selected stations. The maximum and minimum monthly average temperatures were recorded in August 2010 and February 1992, which were 26.89°C and 3.95°C, respectively.

A comparison between the monthly temperatures recorded in each climatic period across Beirut shows that there was a slight increase in the average temperature, particularly in the second climatic period (2001–2010), as shown in Fig. 8.

4.3. Rainfall characteristics

As mentioned previously, the Maximum likelihood method was used to determine the parameters of 10 distribution functions (Table 7).The distribution parameters were estimated using monthly precipitation amounts with

Table 7
Statistical distributions used in the current study

Distribution function	PDF	CDF
Weibull (W)	$\text{PDF} = \left(\frac{k}{c}\right)\left(\frac{p}{c}\right)^{k-1} \exp\left(-\left(\frac{p}{c}\right)^{k}\right)$	$\text{CDF} = 1 - \exp\left(-\left(\frac{p}{c}\right)^{k}\right)$
Rayleigh (R)	$\text{PDF} = \frac{2p}{c^2} \exp\left(-\left(\frac{p}{c}\right)^{2}\right)$	$\text{CDF} = 1 - \exp\left[-\left(\frac{p}{c}\right)^{2}\right]$
Rayleigh (2R)	$\text{PDF} = \frac{p-\gamma}{c^2} \exp\left(-\frac{1}{2}\left(\frac{p-\gamma}{c}\right)^{2}\right)$	$\text{CDF} = 1 - \exp\left(-\frac{1}{2}\left(\frac{p-\gamma}{c}\right)^{2}\right)$
Normal (N)	$\text{PDF} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{p-\mu}{2\sigma^2}\right)$	$\text{CDF} = \frac{1}{2}\left[1 + \text{erf}\left(\frac{p-\mu}{\sigma\sqrt{2}}\right)\right]$
Gamma (G)	$\text{PDF} = \frac{p^{\beta-1}}{\alpha^{\beta}\Gamma(\beta)} \exp\left(-\frac{p}{\beta}\right)$	$\text{CDF} = \frac{\gamma\left(\beta, \frac{p}{\alpha}\right)}{\Gamma(\beta)}$
Lognormal (LN)	$\text{PDF} = \frac{1}{p\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(p)-\mu}{\sigma}\right)^{2}\right]$	$\text{CDF} = \frac{1}{2} + \text{erf}\left[\frac{\ln(p)-\mu}{\sigma\sqrt{2}}\right]$
Logistic (L)	$\text{PDF} = \frac{\exp\left(-\frac{p-\mu}{\sigma}\right)}{\sigma\left\{1 + \exp\left(-\frac{p-\mu}{\sigma}\right)\right\}^{2}}$	$\text{CDF} = \frac{1}{1 + \exp\left(-\frac{p-\mu}{\sigma}\right)}$
Log-Logistic (LL)	$\text{PDF} = \left(\frac{\left(\frac{\beta}{\alpha}\left(\frac{p}{\alpha}\right)^{\beta-1}\right)}{\left(1+\frac{p}{\alpha}\right)^{\beta}}\right)^{2}$	$\text{CDF} = \frac{1}{\left(1+\frac{p}{\alpha}\right)^{-\beta}}$
Gumbel Min. (GMin)	$\text{PDF} = \frac{1}{\sigma} \exp\left(\frac{p-\mu}{\sigma} - \exp\left(\frac{p-\mu}{\sigma}\right)\right)$	$\text{CDF} = 1 - \exp\left(\frac{p-\mu}{\sigma} - \exp\left(\frac{p-\mu}{\sigma}\right)\right)$
Gumbel Max. (G.Max)	$\text{PDF} = \frac{1}{\sigma} \exp\left(-\frac{p-\mu}{\sigma} - \exp\left(-\frac{p-\mu}{\sigma}\right)\right)$	$\text{CDF} = 1 - \exp\left(-\frac{p-\mu}{\sigma} - \exp\left(-\frac{p-\mu}{\sigma}\right)\right)$

W	K	Shape parameter	LL	β	Shape parameter	G.Min/G.Max	σ	Scale parameter
	c (m/s)	Scale parameter		α	Scale parameter		μ	Location parameter
G	β	Shape parameter	2R	γ	Location parameter	N	σ	Standard deviation
	α	Scale parameter		c (m/s)	Scale parameter		μ	Mean parameter
LN	σ	Shape parameter	L	μ	Location Parameter	R	c (m/s)	Scale parameter
	μ	Scale parameter		σ	Scale Parameter			

Table 8
Descriptive statistics of rainfall series

Year	Mean (mm)	Standard deviation	Variance	Coefficient of variation	Minimum (mm)	Maximum (mm)	Skewness	Kurtosis
1991	62.8	71.4	5,100.8	113.79	0	218.6	1.04	0.31
1992	59.8	79.8	6,363.6	133.3	0	228.6	1.29	0.38
1993	34	38	1,445.5	111.96	0	101.5	0.95	-0.64
1994	58.2	67.7	4,583.6	116.35	0	171.6	0.75	-1.25
1995	28.59	31.36	983.47	109.7	0	103.66	1.27	1.72
1996	43.2	48.9	2,395.9	113.18	0	142.9	0.97	-0.22
1997	43.7	40.6	1,644.4	92.71	0	115.7	0.45	-1.19
1998	37.8	48	2,307.1	126.91	0	124.3	0.99	-0.75
1999	22.63	25.86	668.49	114.27	0	73.37	0.92	-0.35
2000	46	65.4	4,278.9	142.34	0	225.8	2.15	5.24
2001	47.4	53.3	2,837.9	112.33	0	145.4	1.05	-0.08
2002	54.8	58.9	3,463.9	107.43	0.1	156.8	0.75	-0.77
2003	73.1	88.4	7,812.3	120.91	0	265.7	1.06	0.26
2004	54.2	76	5,779.4	140.31	0	252.2	1.81	3.54
2005	44	43.1	1,861.8	98.1	0	115.6	0.65	-1.07
2006	37.8	41.8	1,745.5	110.38	0	101.8	0.59	-1.59
2007	40.1	41.4	1,716.2	103.42	0	128.5	0.82	0.1
2008	30.4	37	1,369.1	121.85	0	104.8	1.14	0.09
2009	48.3	53.2	2,828.3	110.05	0	165.6	0.99	0.45
2010	33.1	54.1	2,927.3	163.39	0	148.3	1.48	0.67
2011	52.7	51.1	2,610	96.86	0	141	0.38	–1.46
2012	65.2	75	5,622.8	114.93	0	224.5	1.02	0.18
2013	45.6	65.1	4,236.1	142.61	0	191.9	1.44	0.95
2014	32.13	34.28	1,174.84	106.68	0.06	99.74	0.99	–0.04
2015	35.8	35.4	1,253.6	98.84	0	100.8	0.63	–0.59
Annual	45.3	45.4	2,060.3	100.29	0	123.2	0.57	–1.23

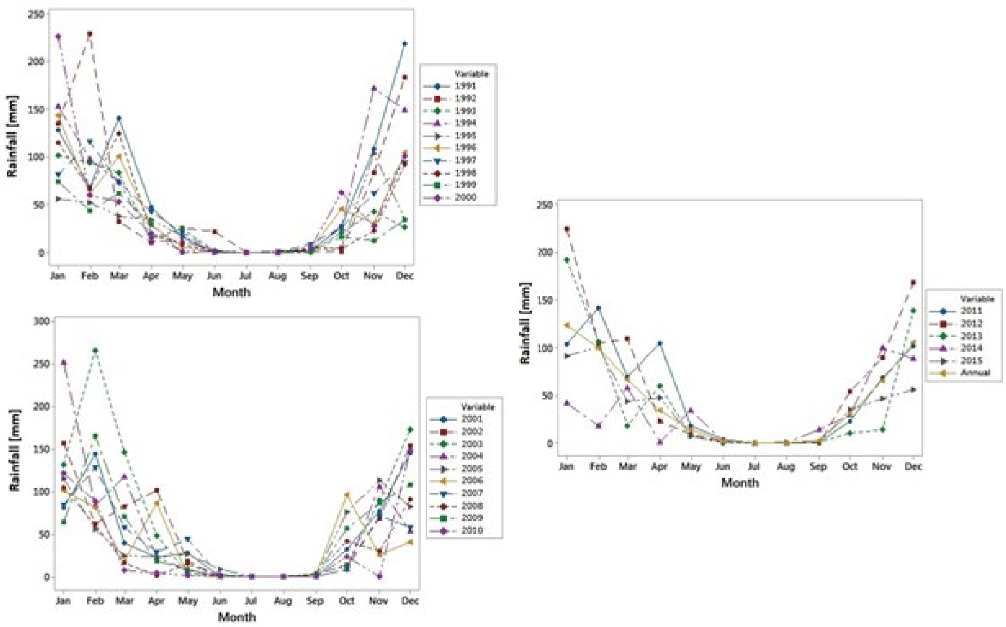

Fig. 4. Monthly rainfall of the three periods: 1991–2000, 2001–2010 and 2011–2015.

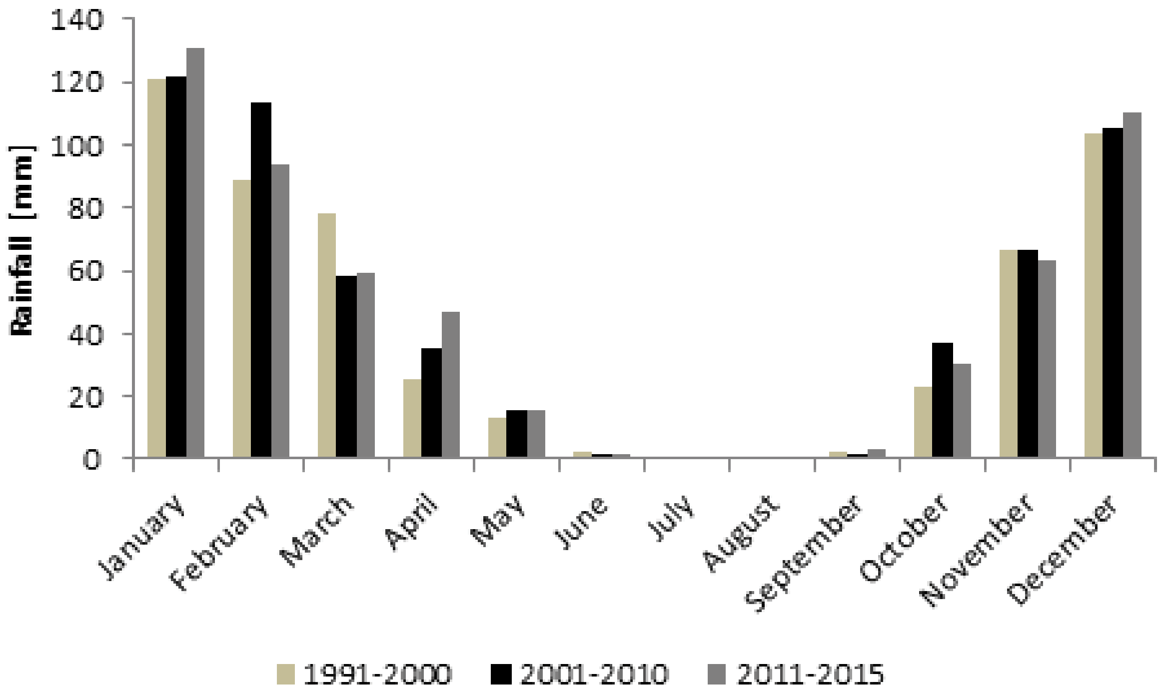

Fig. 5. Comparison of mean monthly rainfall over Beirut.

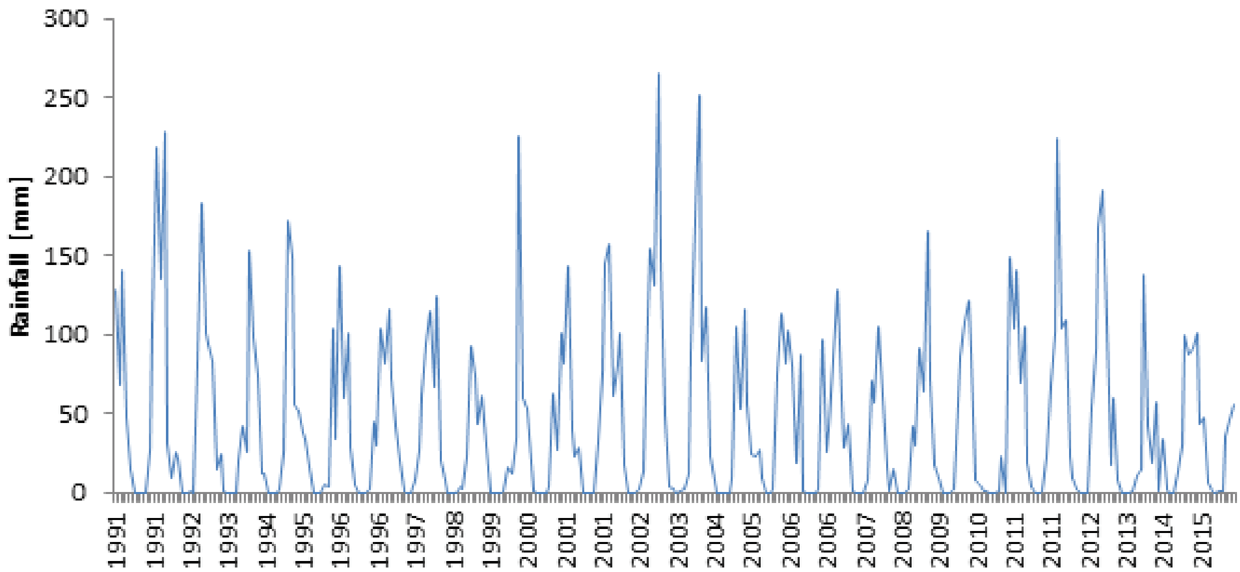

Fig. 6. Annual rainfallduring the investigation period.

the maximum likelihood method. The best distribution among the 10 distribution functions was evaluated with the Kolmogorov–Smirnov test (KS). The calculated parameters of each distribution functions are tabulated in Table 10. Additionally, Fig. 9 shows the best-fitted PDF and CDF model for the observed precipitation data. Furthermore, Table 10 presents the goodness-of-fit statistics in terms of KS for each distribution function. Moreover, a distribution with a minimum value of Kolmogorov–Smirnov will be selected to be the best model for the rainfall distribution in the studied location. Hence, based on KS, G.Max has a minimum value, which is considered as the best

Table 9
Descriptive statistics of the temperature series

Year	Mean (°C)	Standard deviation	Variance	Coefficient of variation	Minimum (°C)	Maximum (°C)	Skewness	Kurtosis
1991	15.9	6.51	42.34	40.92	6.81	23.76	–0.32	–1.45
1992	14.65	7.57	57.31	51.67	3.95	24.82	–0.26	–1.56
1993	15.74	7.16	51.28	45.5	5.77	24.83	–0.08	–1.66
1994	16.59	6.9	47.67	41.61	6.13	24.82	–0.26	–1.65
1995	16.09	6.68	44.56	41.49	7.85	25.29	0.04	–1.79
1996	16.37	6.48	41.99	39.58	7.49	25.17	0.06	–1.65
1997	15.49	6.88	47.3	44.39	5.15	24.79	–0.15	–1.66
1998	16.99	6.92	47.9	40.74	6.48	26.62	–0.21	–1.35
1999	16.85	6.56	42.97	38.9	8.34	25.59	–0.04	–1.78
2000	16.38	7.41	54.92	45.23	6.34	26.61	0.02	–1.56
2001	17.37	6.45	41.64	37.14	8.46	25.97	–0.03	–1.57
2002	16.66	6.97	48.56	41.83	6.22	25.89	–0.07	–1.54
2003	16.88	7.1	50.47	42.09	7.01	26.24	–0.12	–1.82
2004	16.44	6.75	45.55	41.06	6.94	25.38	–0.15	–1.56
2005	16.32	6.4	40.99	39.22	7.86	25.26	0.07	–1.53
2006	15.91	6.61	43.72	41.55	6.97	25.31	0.01	–1.69
2007	16.24	6.96	48.38	42.84	6.84	25.17	–0.05	–1.8
2008	16.6	7.18	51.58	43.25	4.32	25.81	–0.34	–1.03
2009	16.54	6.75	45.62	40.85	7.14	25.13	–0.02	–1.77
2010	17.98	6.2	38.4	34.46	10.01	26.9	–0.03	–1.55
2011	15.82	6.84	46.74	43.22	7.72	25.4	0.19	–1.73
2012	16.68	7.39	54.58	44.29	6.48	26.05	–0.21	–1.65
2013	16.15	5.92	35.09	36.68	7.09	24.2	–0.21	–1.32
2014	16.51	5.55	30.85	33.65	9.24	24.75	0.08	–1.54
2015	16.34	6.79	46.06	41.54	7.02	25.79	0.02	–1.52
Annual	16.38	6.68	44.59	40.77	7.43	25.19	–0.06	–1.68

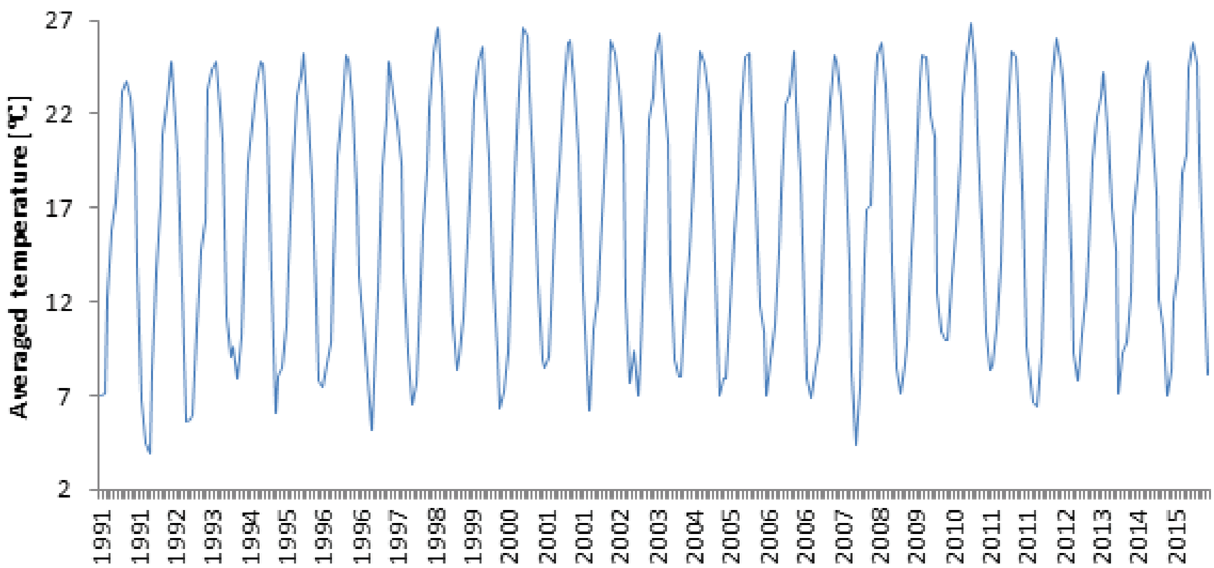

Fig. 7. Monthly averaged temperature during the investigation period.

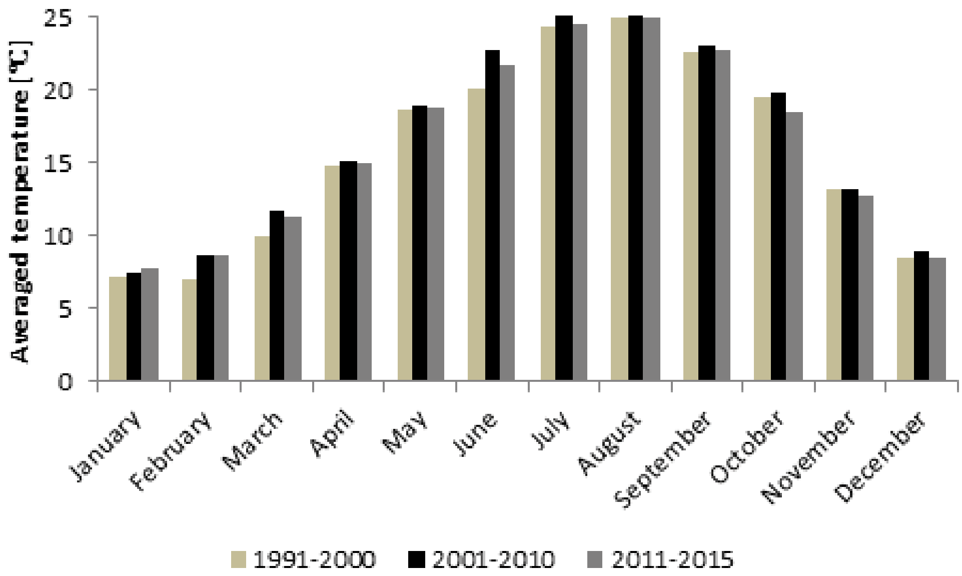

Fig. 8. Comparison of mean monthly averaged temperature over Beirut.

Table 10
Parameter values of different distribution function and results of goodness-of-fit

Model	Parameter	Value	KS	Rank
W		0.3519	0.22493	5
		34.6288		
R		36.1129	0.34045	10
2R		59.6863	0.21864	4
		–27.1006		
N		45.3919	0.18215	2
		45.2608		
G		0.9942	0.28181	9
		45.5235		
LN		2.9296	0.24287	7
		2.1978		
L		25.0259	0.19491	3
		45.2688		
LL		0.45212	0.24043	6
		7.0998		
G.Min		35.3919	0.24878	8
		65.6896		
G.Max		35.3919	0.18180	1
		24.8320		

distribution function to study the rainfall characteristics of the studied station.

The relationship between the air temperature and the rainfall during the investigation period (1991–2015) is shown in Fig. 10. It is observed that there was a positively significant interaction between rainfall and temperature. It is found that a decrease in the air temperature led to an increase in the precipitation amount in the selected region.

5. Conclusions

The review aimed to assess the water resources in Lebanon focused on drinking, industrial, and irrigation water. One of the primary sources of surface water is rainfall, thus climate data in terms of rainfall and the air temperature of Beirut area for the period from 1991 to 2015 were analyzed statistically to evaluate the different climatic environments in the capital city, Beirut. In addition, monthly mean rainfall data were modeled using 10 distribution functions to forecast the behavior of rainfall. The maximum likelihood method was used to estimate the parameters and it was found that the Gumbel Maximum and Logistic distributions are more appropriate for the studied area.

Although Lebanon is a country richer in water resources than other countries in the region, increasing demand for water, inefficient management practices, fragmented institutional framework and lawlessness mean chronic water shortages are possible in the future. As mentioned in this report, efforts and plans to improve water management are at the government level. In addition to ministerial strategies and plans, other promising initiatives are underway, such as a project to establish a national information system as a common database to integrate all available information on the state of surface and groundwater. It also highlights a particularly important point that the implement of new water laws has been ongoing since 2005, which aims to address a series of governance, institutional and administrative issues and recommended provisions for the implementation of the sustainable management of water resources in the country in terms of quantity and quality. Apart from government efforts and small-scale internationally funded initiatives aimed at conserving water, the role and influence of civil society

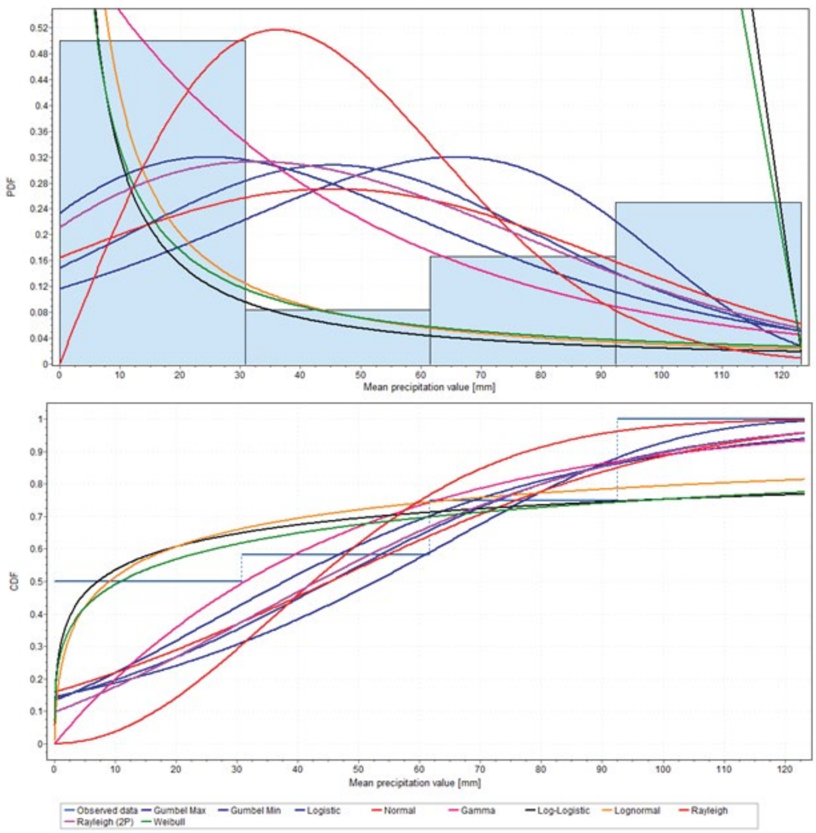

Fig. 9. Fitting PDF and CDF models to the annual rainfall value of Beirut during the investigation period.

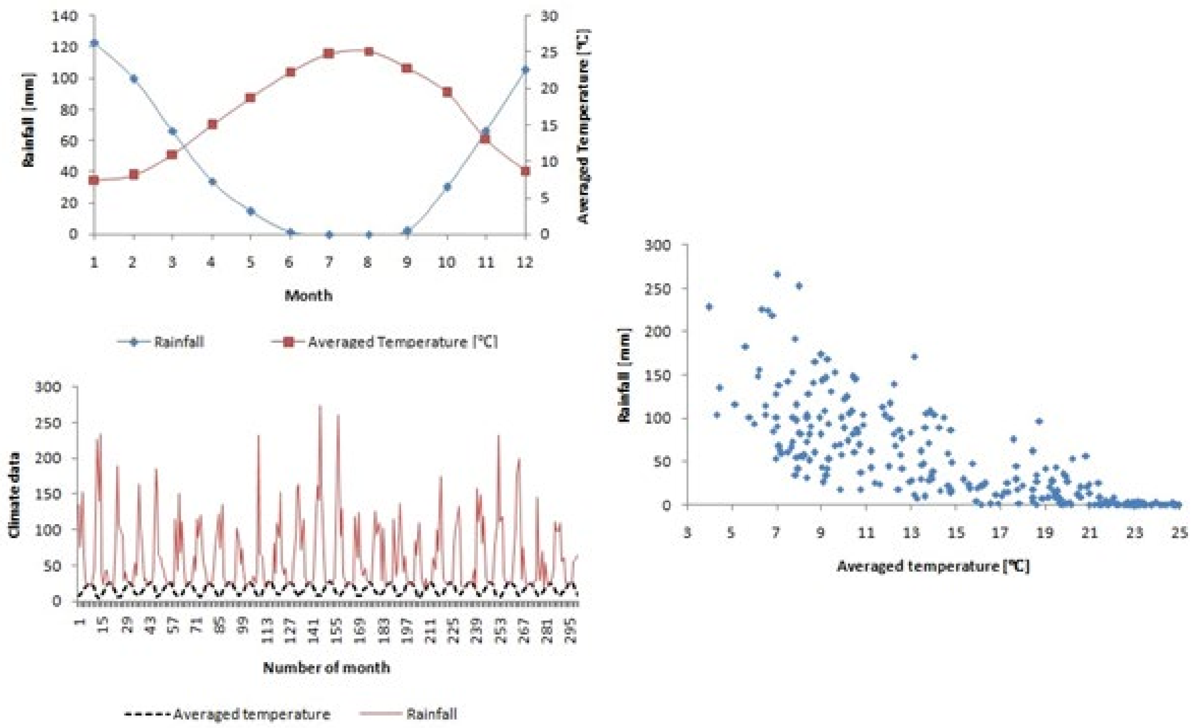

Fig. 10. Monthly mean of the meteorological data over 25 years from 1991 to 2015.

has gained momentum, with initiatives such as the Blue Gold project by the Civil Impact Forum and civil society to oppose controversial government plans to build new dams. Moreover, the growing water crisis in Lebanon, which combines natural, institutional and geopolitical challenges, must be urgently addressed. This not only requires a comprehensive administrative framework but also a strong political will, with a focus on addressing the rapidly deteriorating situation and ensuring the long-term sustainability of resources. Moreover, the potential threats of climate change render the situation more urgent.

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