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The Necessity of Updating IDF Curves for the Sharjah Emirate, UAE: A Comparative Analysis of 2020 IDF Values in Light of Recent Urban Flooding (April 2024)

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Abstract: In the arid Arabian Peninsula, particularly within the United Arab Emirates (UAE), the perception of rainfall has shifted from a natural blessing to a significant challenge for infrastructure and community resilience. The unprecedented storm on 17 April 2024, exposed critical vulnerabilities in the UAE's urban infrastructure and flood management practices, revealing substantial gaps in handling accumulated precipitation. This study addresses the necessity of updating the Intensity–Duration–Frequency (IDF) curves for the Sharjah Emirate by utilizing recent precipitation data from 2021 to April 2024, alongside previously published 2020 data. By recalibrating the IDF curves based on data from three meteorological stations, this study reveals a substantial increase in rainfall intensities across all durations and return periods. Rainfall intensities increased by an average of 36.76% in Sharjah, 26.52% in Al Dhaid, and 17.55% in Mleiha. These increases indicate a trend towards more severe and frequent rainfall events, emphasizing the urgent need to revise hydrological models and infrastructure designs to enhance flood resilience. This study contributes valuable insights for policymakers, urban planners, and disaster management authorities in the UAE and similar regions worldwide.

Keywords: intensity–duration–frequency (IDF) curves; update; urban floods; rainfall; Sharjah City; the UAE

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Citation: Almheiri, K.B.; Rustum, R.; Wright, G.; Adeloye, A.J. The Necessity of Updating IDF Curves for the Sharjah Emirate, UAE: A Comparative Analysis of 2020 IDF Values in Light of Recent Urban Flooding (April 2024). *Water* **2024**, *16*, 2621. https://doi.org/10.3390/w16182621

Academic Editor: M. Levent Kavvas

Received: 29 June 2024
Revised: 5 September 2024
Accepted: 13 September 2024
Published: 15 September 2024

1. Introduction

In the arid region of the Arabian Peninsula, particularly within the UAE, the long-anticipated arrival of rain has shifted from being a natural blessing to becoming a formidable and hazardous event. What was once a welcomed event has become intertwined with urban floods, steadily intensifying in both amount and depth, thereby posing a growing threat to the community and the surrounding environments. The rainfall occurrences on 17 April 2024, in the UAE highlighted significant vulnerabilities in the nation's infrastructure and community readiness. According to the Emirates News Agency, WAM, this event exceeded any previously recorded rainfall since data collection began in 1949 [1]. Substantial shortcomings were revealed in the drainage systems' capacity to manage storm runoff effectively. Extensive urban regions experienced unprecedented flooding, surpassing previous records and lasting expectations. Instances of complete ground-floor submersion of residential properties were observed across various regions of the country, as depicted in Figure 1a,b. Major and local road blockages remained for several days, as evidenced in Figure 2a,b. Vehicles submerged entirely were a ubiquitous sight, illustrated in Figure 3a,b. Moreover, without exception, all wadis reverted to their original courses, some of which had not been seen for decades. Notably, a significant wadi, originating from the eastern mountains between the UAE and Oman and terminating at the Gulf in Umm Al Quwain city in the north, caused substantial damage to roads and water tunnels inadequately equipped to manage its actual capacity and variability, as illustrated in Figure 4a,b.

(**a**) (**b**)

Figure 1. (**a**,**b**) The submersion of ground floors in residential properties.

(**a**) (**b**)

Figure 2. (**a**,**b**) The submergence of major roads due to rainwater.

(**a**) (**b**)

Figure 3. (**a**,**b**) Vehicles partially and fully submerged.

Consequently, nationwide schools became inaccessible, prompting a transition to online education for over four days across all cities, with an extension to six days for schools in flood-affected areas. Similarly, government departments implemented a shift to online work arrangements for all employees nationwide, spanning four days from the onset of the rainstorm. Regrettably, official reports have confirmed the loss of a life resulting from a sink accident in Wadi Isfni, located within the southern regions of Ras

Al Khaimah [2]. This was a time of significant impact, as detailed in this paper. The briefly documented findings above can serve as valuable references for future research and exploration, addressing the tangible and complex contexts of this topic.

(**a**) (**b**)

Figure 4. (**a**,**b**) Two roads impacted by the destructive wadi.

Considering the vast and unprecedented impacts of the April 2024 urban floods on the UAE and the surrounding region compels us, as researchers and specialists in this field, to take a stance on the distressing circumstances that revealed vulnerabilities in the mechanical operations of drainage infrastructure and underscored the significance of the findings and recommendations derived from valuable research conducted over the past decade. A previous study by Almheiri et al. (2021) analyzed the influence of cloud-seeding operations on IDF curve values and proposed two significant recommendations to mitigate potential urban flood impacts in the region [3]. These recommendations encompassed a re-evaluation of the comprehensive functionality of urban stormwater drainage systems as essential components of city development and the regular updating of IDF data to accommodate evolving climatic conditions. Furthermore, the study emphasized the importance of assessing the broader ramifications of these changes, particularly on the efficacy and functionality of storm drainage networks within the urban environment.

In the UAE, the precision and reliability of hydrological assessments are critically constrained by the limited historical meteorological data, especially concerning IDF curves [3]. These curves are crucial for analyzing how rainfall intensity varies with its duration and frequency, providing essential data for accurately predicting extreme weather events and designing systems that can effectively manage and mitigate flood risks. The scarcity of comprehensive, long-term rainfall data has hindered the accurate formulation of these assessments. This limitation has become particularly evident through the recurrent failures of hydrological infrastructure to adequately manage and respond to rainfall events over the past decade [4]. This underscores the urgent need for updated and more accurate IDF curves to enhance infrastructure resilience and improve flood management practices in the face of changing weather patterns.

The situation is further complicated by the impacts of climate change, which introduce significant variability in rainfall intensity, frequency, and overall weather patterns. The increasing unpredictability of climatic conditions necessitates regular updates to IDF curves to ensure they reflect these evolving climatic shifts accurately [5]. Existing IDF curves are increasingly inadequate as shifts in hydro-climate variables, such as rainfall and temperature, no longer align with current conditions or account for recent trends in urban development [6]. As climate patterns become more erratic and extreme weather events become more frequent, the necessity for revising these curves is more pressing than ever.

Furthermore, urban expansion profoundly affects hydrological dynamics, necessitating updates to IDF curves to accurately represent changes in land use [7]. As cities grow and land use patterns shift, the hydrological response of regions evolves, requiring precise adjustments to IDF curves. Incorporating the latest meteorological data into these curves is crucial for advancing flood risk management, supporting strategic urban planning, and enhancing preparedness for extreme weather events. Accurate IDF curves are essential for effectively addressing the rapidly changing environmental conditions in the UAE. By ensuring that infrastructure and flood management strategies are based on the most up-to-date information, cities can develop resilient and cutting-edge systems capable of confronting the challenges posed by both climate change and accelerated urbanization.

This study is set to advance the understanding of evolving weather patterns and their implications for urban floods and aims to update the IDF curve values for the Sharjah Emirate, utilizing the latest precipitation data from 2021 to April 2024. By integrating these recent datasets with existing historical records that span from 1992 to 2020, the IDF curves will be recalibrated and compared with previous values across three distinct meteorological stations. This comprehensive approach enables the refinement of flood risk assessments and enhances infrastructure planning, ensuring that current and future urban development is supported by the most accurate and up-to-date hydrological data.

2. Methodology

2.1. Description of the Study Area

Sharjah, situated within the UAE, is recognized as the third-largest emirate in the country, encompassing a total land area of 2600 square kilometers. Geographically, it is positioned approximately between 25.2° N to 25.4° N and 55.4° E to 55.6° E. Sharjah serves as a pivotal urban hub, bordered by Ajman and Al Um Al Quwain to the north, Fujairah and Ras Al Khaimah to the east and southeast, Dubai to the south, and the Arabian Gulf to the west (refer to Figure 5). The emirate comprises three distinct regions: Sharjah City in the west, the central region, and the mountainous eastern region. This paper will focus on Sharjah City and the central region, following the approach of the 2021 baseline study [3].

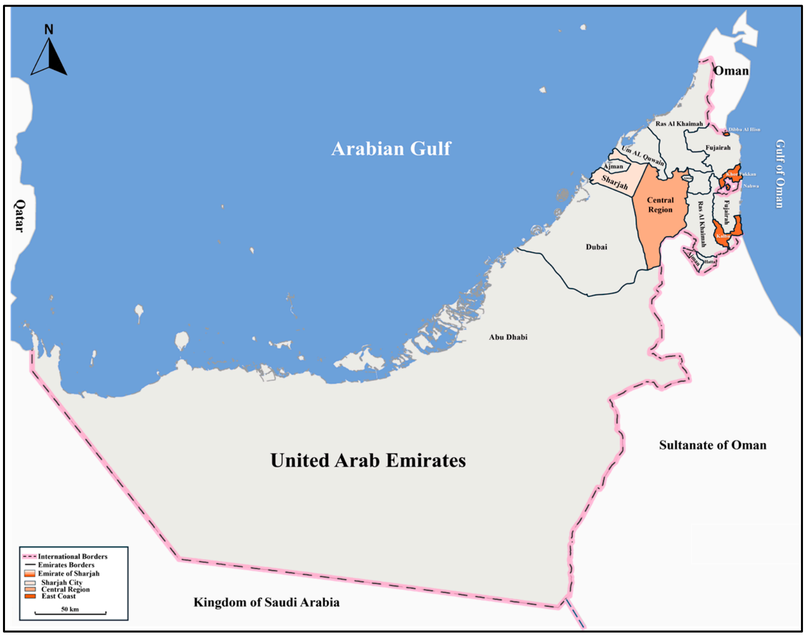


Figure 5. Map of the UAE showing the location of the Sharjah Emirate and its three regions [8].

2.2. Data Collection

The previous study [3] utilized rainfall data from three meteorological stations within the Sharjah Emirate, as detailed in Table 1 [9–13].

Table 1. Meteorological station coordinates and rainfall observation dates.

Station Name	Altitude (M amsl)	Coordinates		Original Records Duration	Extended Records Duration "Previous Paper"	Newly Added Records Duration
		Longitude	Latitude			
Sharjah Airport	34	55° 31 02 E	25° 19 43 N	16 September 2014–31 May 2020	1 January 1992–31 May 2020	1 June 2020–17 April 2024
Al Dhaid	111	55° 49 01 E	25° 14 13 N	1 March 2010–31 May 2020		
Mleiha	186	55° 53 17 E	25° 07 50 N	1 January 2003–31 May 2020		

These stations, located in Sharjah City, Al Dhaid, and Mleiha, as shown in Figure 6, were strategically chosen to capture diverse geographical perspectives, ensuring unbiased results concerning IDF curve values and comprehensively depicting trends. As indicated in Table 1, the initially acquired hourly records for each station were limited to the years 2014 in Sharjah, 2010 in Al Dhaid, and 2003 in Mleiha. However, data from the nearby Dubai Airport spanning from 1992 were employed to address gaps in the dataset. The multivariate self-organizing map (SOM) artificial neural network was employed to interpolate missing data for the Sharjah stations. Detailed information on the application of a self-organizing map for data infilling can be found in references [9–13]. As of 17 April 2024, these records have been updated to facilitate comparative analysis following recent flooding events in the UAE.

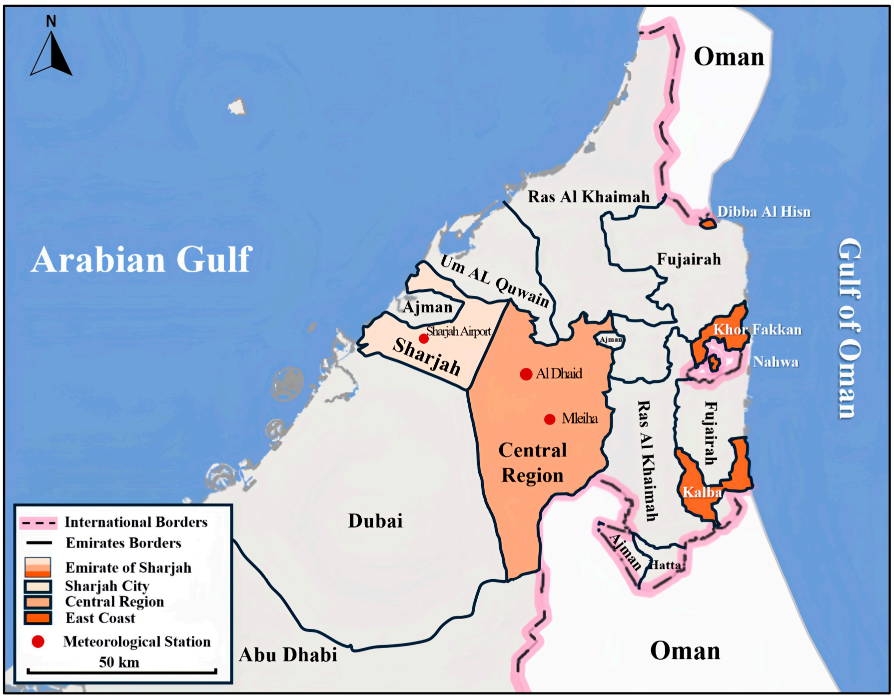


Figure 6. Map of the Sharjah Emirate showing the locations of the meteorological stations used in this study [8].

This study employs a rigorous methodology to update the IDF curve values for three meteorological stations in Sharjah, utilizing the latest rainfall data from the past three years and four months alongside historical records. The updated IDF values will be compared to the 2020 values for each station independently. This methodology aims to achieve three primary objectives: first, to build upon the approach established in the previous study; second, to minimize bias by analyzing data from three distinct meteorological stations situated in different geographical locations; and third, to assess changes in IDF curve values, whether increases or decreases.

The Gumbel Distribution is employed to characterize extreme rainfall events at these stations. Additionally, statistical analyses are conducted using historical rainfall data to determine the 24 h annual maximum and mean annual rainfall figures. These results are fundamental for generating updated IDF curves and enabling a comparative statistical assessment against previous data. The findings will be disseminated for the benefit of researchers and other stakeholders.

The entire process is implemented using the HyFran-Plus Version 2.1 frequency analysis software tool [14]. This comprehensive approach underscores the necessity of regularly updating IDF curves to effectively address the evolving hydrological conditions and support robust flood risk management and infrastructure planning at both local and regional levels.

2.3. Frequency Analysis

To analyze the frequency of extreme rainfall events, we use the Weibull formula (1) to calculate the probability P of exceeding each ranked annual maximum rainfall:

$$\mathrm{P} = \frac{Rank - a + b}{(n+1) - 2a + b}, \tag{1}$$

where a and b are set to zero, and n is the number of years. The return period T, the average interval in years between storms of a given magnitude, is then determined by Equation (2):

$$\mathrm{T} = \frac{1}{P}, \tag{2}$$

Using historical rainfall data, we rank maximum daily rainfall depths and calculate the probability of exceedance and corresponding return periods. The HyFran-Plus Version 2.1 software [14] is employed for this frequency analysis, using Weibull and Gumbel distributions to fit the data, specifically focusing on a 100-year return period for the estimations in this study.

The maximum daily rainfall depth for any given return period was calculated based on the best-fitting distribution. Following the World Meteorological Organization (WMO) 2009 guidelines [15], daily rainfall amounts are adjusted by a factor of 1.13 to correct for observational biases.

For different return periods, the rainfall intensities over various durations (e.g., 10 min, 20 min, 30 min, 60 min, 120 min) were computed using depth–duration ratios derived from Frederick and Bell (1969) [16]. The depth–duration ratio is given by Equation (3):

$$\frac{PT^{t}}{PT^{60}} = 0.54t^{0.25} - 0.50 \;\; if \;\; 5 \le t \le 120, \tag{3}$$

where PT^t is the rainfall depth at duration t, and PT^{60} is the maximum 60 min rainfall depth.

Finally, the IDF curves were developed by plotting the computed IDF values, providing critical insights into the intensity and frequency of rainfall events. These steps are instrumental in evaluating historical rainfall data and predicting future trends, ensuring robust planning and management of water resources [3].

2.4. Statistical Analysis of IDF Curve Fitting

Updating IDF curve values requires a thorough statistical analysis to ensure precision and reliability. This process involves fitting rainfall data to appropriate probability distributions to derive accurate IDF curves for the Sharjah Emirate.

The Gumbel Distribution is employed to model extreme rainfall events due to its proven effectiveness in capturing such extremes. The IDF curves are generated by analyzing annual maximum rainfall data from three meteorological stations across the Sharjah Emirate, as detailed in Section 2.2. The data used include rainfall records from January 1992 to April 2024. The analysis is conducted using the HyFran-Plus Version 2.1 frequency analysis software [14], which facilitates the statistical fitting of data to both Weibull and Gumbel distributions.

The process begins with ranking the annual maximum daily rainfall depths to compute the probability of exceedance. This probability is crucial for determining the return period, which represents the average time interval between rainfall events of a given magnitude. The analysis then calculates the return period and associated rainfall intensities for various durations, ranging from 10 to 120 min. These data are essential for updating the IDF curves, which illustrate variations in rainfall intensity across different durations and return periods.

To ensure the robustness of the IDF curves, depth–duration ratios are calculated. These ratios account for variations in rainfall duration and ensure that the IDF curves accurately reflect realistic rainfall patterns. The ratios are derived from established guidelines and used to refine the IDF values.

A significant advancement in this study is the use of the multivariate self-organizing map (SOM) neural network, which was employed in our previous paper, as referenced in Section 2.2. This approach has provided an extended and reliable set of historical rainfall records for Sharjah City, synthesizing an additional 21 years of hourly rainfall data for the three meteorological stations. This improvement enhances the efficacy and reliability of future design studies in the study area, as discussed by Almheiri et al. (2021) [3]. By effectively addressing the issue of incomplete and missing data in historical meteorological records, the SOM neural network offers effective solutions for infilling these records, significantly improving the comprehensiveness of the dataset.

Overall, the rigorous statistical fitting and analysis ensure that the updated IDF curves for the Sharjah Emirate are based on the most recent and comprehensive rainfall data, accurately reflecting current hydrological conditions. This approach provides valuable insights into rainfall frequency and intensity, supporting effective flood risk management and infrastructure planning.

3. Results and Discussion

The IDF curves are essential for understanding rainfall characteristics and estimating frequency and intensity. Recent high rainfall in the Sharjah Emirate has raised concerns about the adequacy of existing IDF values to reflect changing precipitation patterns. Updated IDF curves for the Sharjah Airport, Al Dhaid, and Mleiha stations were compared with 2021 values. The revised figures show a significant rise, likely due to long-term climate oscillations rather than cloud seeding. This finding aligns with Modabbermm-Azizi et al. [17], who observed similar variability in Iran. Recent rainfall records in the UAE have surpassed all previous levels since data collection began in 1949.

The comprehensive rainfall dataset spanning from 1992 to 2020, which was collected and analyzed previously [3], is summarized in Table 2. Table 3 documents the corresponding records up to 30 April 2024, providing an up-to-date depiction of rainfall patterns. These updated records have not only contributed to establishing a robust climatological database but have also served as inputs for calculating the updated IDF curve values for the Sharjah Emirate, as discussed in Section 3.1.

Significantly, the NEW IDF values, updated with additional rainfall data from January 2021 to April 2024, have exceeded all previous OLD IDF values, which are based on rainfall records from January 1992 to 2020, as compared in Table 4. These findings underscore the significance of recording and updating meteorological data, particularly in a country like the UAE, where past records are relatively limited and a comprehensive understanding of rainfall intensity fluctuations is still developing.

Table 2. Maximum daily rainfall depths (mm) across three stations (1992–2020).

Year	Sharjah	Al Dhaid	Mleiha
1992	11.4	8.3	5.1
1993	2.4	0	0
1994	2.4	15	61.3
1995	32.8	53.5	156.7
1996	16	26.6	121.1
1997	13	24.6	92.4
1998	14.3	24.3	43.5
1999	4.8	30.1	88.6
2000	10.1	26.8	71.7
2001	2.4	15.7	47.8
2002	5.9	14.2	44.3
2003	10.1	11	23.8
2004	7.6	5.8	9.8
2005	17.4	6.1	12.2
2006	7.4	37.3	18.2
2007	0.4	2.6	24
2008	61	41	50.4
2009	26.9	11.7	18.6
2010	24.3	36.8	22.2
2011	11.7	17	17.8
2012	5.5	30.2	62.6
2013	10.3	26.6	29.6
2014	6.5	14	34.8
2015	37.4	5.5	13.6
2016	13.5	140.8	461
2017	10.9	17.2	146.8
2018	78.2	7.2	25
2019	39.8	10.6	28.8
2020	53.9	41.2	64.3
Mean	18.6	24.2	61.9

Table 3. Maximum daily rainfall depths (mm) across three stations (2020–30 April 2024).

Year	Sharjah	Al Dhaid	Mleiha
2021	13.2	12.7	17.7
2022	32.2	33.3	39.8
2023	44	62	55
2024	123.8	153.2	163.4
Mean	53.3	65.3	69.0

Table 4. Comparison of NEW [1] 2024 IDF curve values with OLD [2] 2020 data.

Return Period	City		IDF Curve Values over Different Durations (mm/h)				
			10 min	20 min	30 min	60 min	120 min
2	Sharjah	OLD	25.09	17.50	13.88	9.11	5.85
		NEW	34.96	24.38	19.34	12.70	8.15
	Al Dhaid	OLD	31.92	22.26	17.66	11.59	7.44
		NEW	44.24	30.85	24.47	16.07	10.31
	Mleiha	OLD	73.10	50.98	40.44	26.55	17.04
		NEW	92.66	64.62	51.25	33.65	21.60

Table 4. *Cont.*

Return Period	City		IDF Curve Values over Different Durations (mm/h)				
			10 min	**20 min**	**30 min**	**60 min**	**120 min**
3	Sharjah	OLD NEW	39.32 55.46	27.42 38.68	21.75 30.68	14.28 20.14	9.16 12.93
	Al Dhaid	OLD NEW	51.19 70.69	35.70 49.30	28.32 39.10	18.59 25.67	11.93 16.48
	Mleiha	OLD NEW	127.13 158.69	88.65 110.66	70.32 87.78	46.17 57.63	29.63 36.98
5	Sharjah	OLD NEW	55.42 78.30	38.65 54.60	30.66 43.31	20.13 28.43	12.92 18.25
	Al Dhaid	OLD NEW	73.48 100.15	51.24 69.84	40.65 55.40	26.68 36.37	17.13 23.34
	Mleiha	OLD NEW	190.78 232.23	133.05 161.95	105.53 128.46	69.28 84.34	44.46 54.12
10	Sharjah	OLD NEW	77.70 106.99	54.19 74.61	42.98 59.18	28.22 38.85	18.11 24.94
	Al Dhaid	OLD NEW	104.84 113.17	73.11 78.92	57.99 62.60	38.07 41.10	24.43 26.38
	Mleiha	OLD NEW	285.23 324.64	198.91 226.39	157.77 179.57	103.58 117.89	66.48 75.66
20	Sharjah	OLD NEW	99.80 134.51	69.60 93.81	55.20 74.40	36.24 48.85	23.26 31.35
	Al Dhaid	OLD NEW	136.19 172.68	94.98 120.42	75.33 95.52	49.46 62.71	31.74 40.25
	Mleiha	OLD NEW	379.68 413.28	264.78 288.21	210.02 228.60	137.88 150.08	88.49 96.32
50	Sharjah	OLD NEW	128.82 170.14	89.84 118.65	71.26 94.11	46.78 61.79	30.02 39.65
	Al Dhaid	OLD NEW	177.56 218.64	123.83 152.47	98.22 95.52	64.48 79.40	41.38 50.96
	Mleiha	OLD NEW	508.13 528.01	354.35 368.22	281.07 292.07	184.53 191.75	118.43 123.06
100	Sharjah	OLD NEW	150.73 196.83	105.11 137.27	83.37 108.88	54.74 71.48	35.13 45.87
	Al Dhaid	OLD NEW	209.67 253.08	146.22 176.49	115.98 139.99	76.14 91.91	48.87 58.98
	Mleiha	OLD NEW	606.35 613.99	422.85 428.18	335.40 339.62	220.20 222.97	141.32 143.10

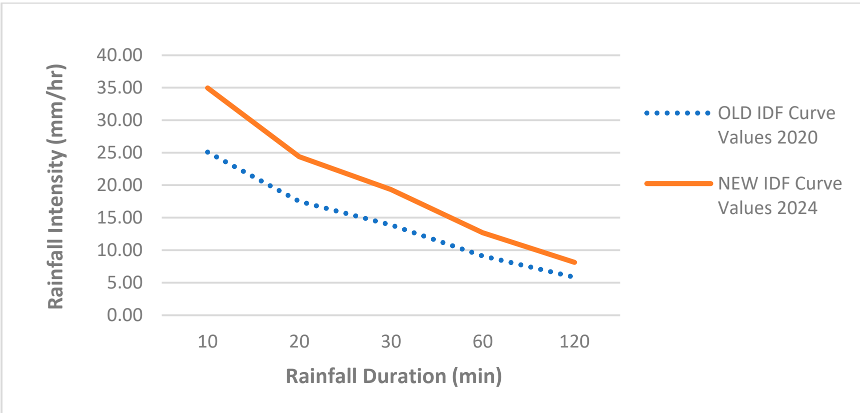
Note(s): [1] NEW: IDF values updated with additional rainfall data from January 2021 to April 2024. [2] OLD: IDF values from 2020, based on January 1992 to 2020 rainfall records.

3.1. Analysis of Updated IDF Curve Values in Sharjah City, Al Dhaid, and Mleiha

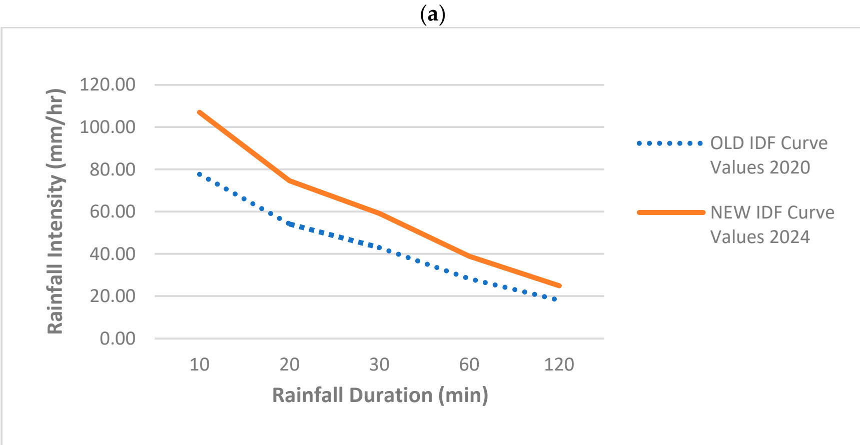
Table 4 provides a detailed overview of IDF curve values for various durations (10, 20, 30, 60, and 120 min) and return periods (2, 3, 5, 10, 20, 50, and 100 years) for three distinct locations: Sharjah City, Al Dhaid, and Mleiha. The data are divided into two categories: OLD and NEW, as mentioned in Section 3 above. This division enables a comparative analysis to evaluate the impact of recent high rainfall records on IDF curves and to provide insights into potential changes in precipitation patterns due to extreme weather. It is important to note that each station is studied independently and compared within the old and new datasets rather than comparing values across different stations. The following subsections will illustrate the statistical comparison of OLD and NEW IDF curve values for each station under study.

3.1.1. Sharjah City

A comparison of IDF curve values between OLD and NEW records for Sharjah City reveals a significant increase in rainfall intensities across all durations and return periods. This trend is particularly pronounced for shorter durations (10 and 20 min) and lower return periods (2 and 3 years). For example, for a 2-year return period, the 10 min duration increased from 25.09 mm/h to 34.96 mm/h, representing a 39.3% rise, while the 60 min duration increased from 9.11 mm/h to 12.70 mm/h, showing a 39.4% rise. These changes are illustrated in Figure 7a.



(**a**)



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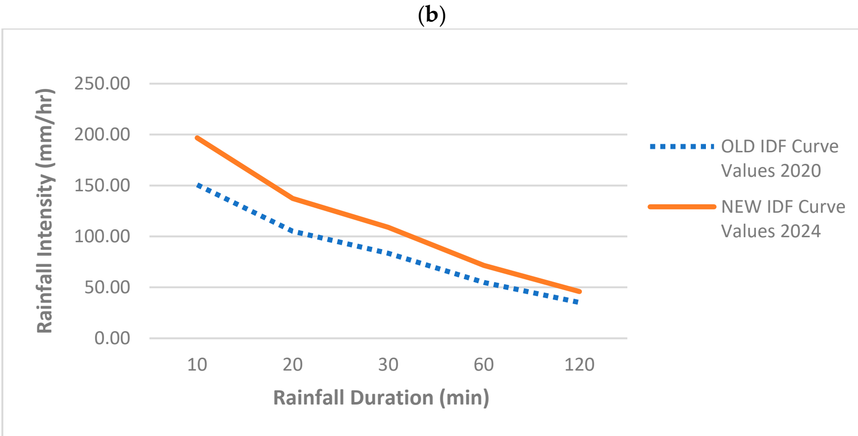
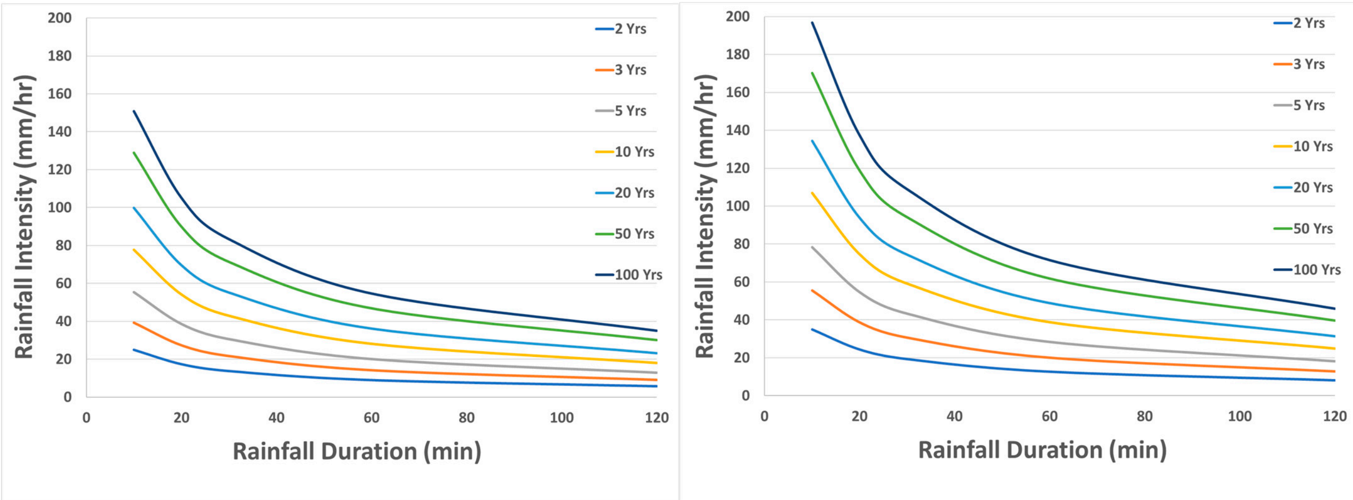


(**c**)

Figure 7. *Cont.*



(**d**) (**e**)

Figure 7. (**a**) The increase in IDF curve values for a 2-year return period in Sharjah City. (**b**) The increase in IDF curve values for a 10-year return period in Sharjah City. (**c**) The increase in IDF curve values for a 100-year return period in Sharjah City. (**d**,**e**) OLD and NEW IDF curve values for Sharjah City, respectively.

Figure 7a presents the increase in IDF curve values for a 2-year return period in Sharjah City. A clear upward shift in the intensity–duration curve is observed, indicating a notable increase in rainfall intensity. This suggests that Sharjah City is experiencing more intense rainfall events even for shorter durations, and this trend needs to be considered in urban planning and flood management.

Figure 7b demonstrates the increase in IDF curve values for a 10-year return period. Similar to Figure 7a, a clear upward shift in the curve is seen, indicating an increase in rainfall intensity. For example, the 30 min duration for a 10-year return period increased from 42.98 mm/h to 59.18 mm/h, reflecting a 37.7% rise. This suggests that the trend of increased rainfall intensity is not limited to shorter return periods but also applies to longer return periods.

Figure 7c shows the increase in IDF curve values for a 100-year return period. Again, a consistent upward shift in the curve is noted, suggesting a continued trend of increasing rainfall intensity even for the longest return period considered. For the 30 min duration, the intensity rose from 83.37 mm/h to 108.88 mm/h, representing a 30.6% increase.

These trends suggest that Sharjah City is experiencing increasingly intense rainfall events, highlighting evolving climate patterns in the region. An overall comparison of the OLD and NEW IDF curve values reveals significant increases in rainfall intensities across various return periods, indicating a shift towards more severe rainfall. This shift is depicted in Figure 7d for the OLD values and Figure 7e for the NEW values.

Figure 7e displays the updated IDF curves, highlighting a consistent and notable increase in rainfall intensities across various return periods and durations. This pattern clearly indicates a rising frequency and intensity of rainfall events over time, underscoring a growing vulnerability of Sharjah City's infrastructure and systems to more severe rainfall. The observed changes emphasize the urgent need for enhanced adaptation and resilience strategies to effectively mitigate the potential impacts of these more intense events. A thorough understanding of these trends is essential for effective future planning and risk management.

3.1.2. Al Dhaid

A comparison of IDF curve values between OLD and NEW values for Al Dhaid reveals a significant increase in rainfall intensities across all durations and return periods. Similar to the analysis conducted for Sharjah City, this trend is particularly pronounced for shorter durations (10 and 20 min) and lower return periods (2 and 3 years). For example, for a 2-year return period, the 10 min duration increased from 31.92 mm/h to 44.24 mm/h, reflecting a 38.6% rise, while the 60 min duration rose from 11.59 mm/h to 16.07 mm/h, a 38.7% increase. These changes are illustrated in Figure 8a.

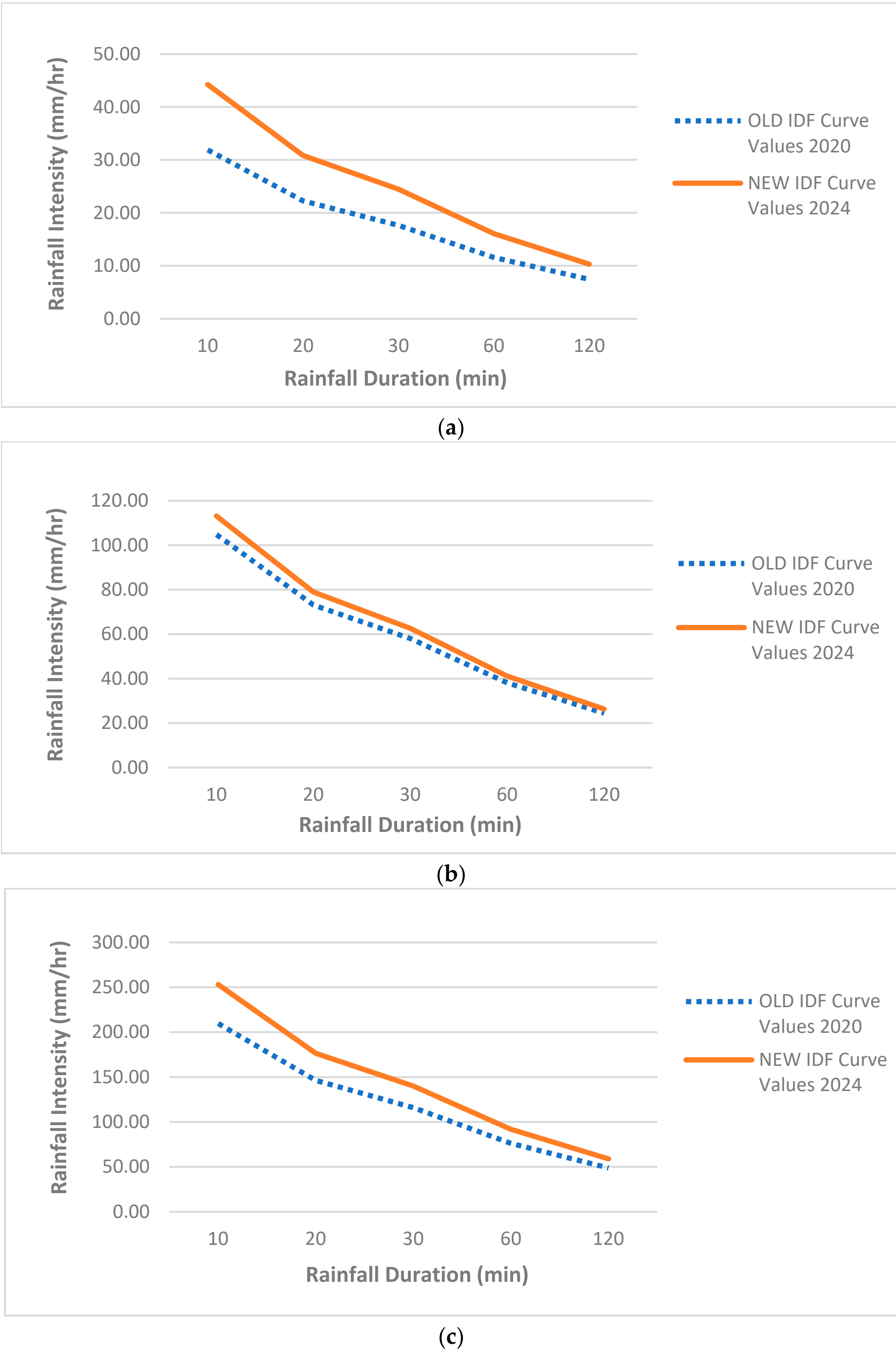
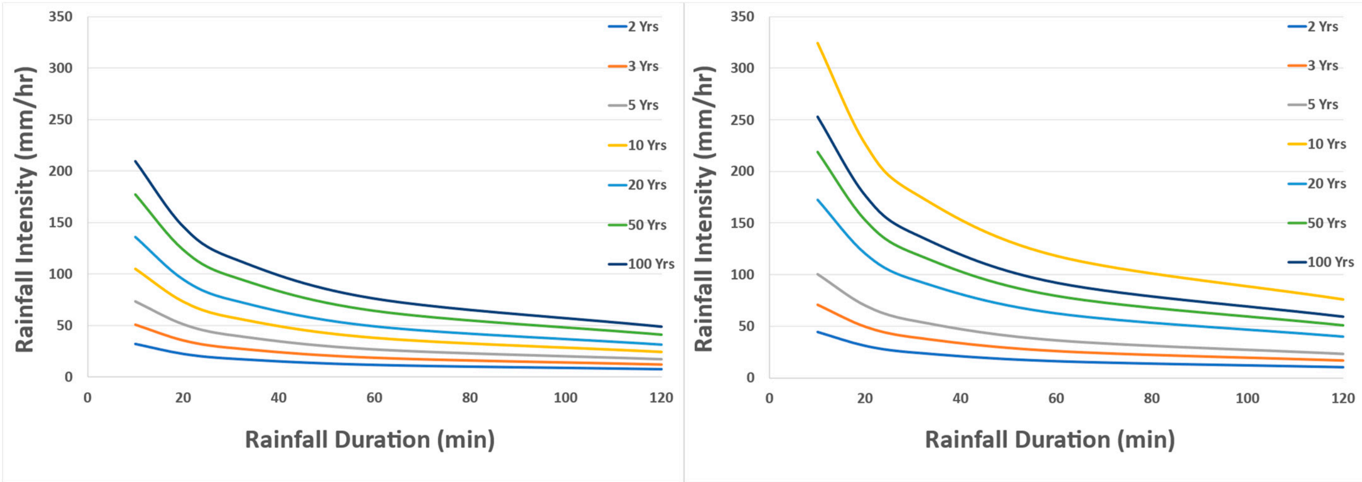


Figure 8. *Cont.*



(**d**) (**e**)

Figure 8. (**a**) The increase in IDF curve values for a 2-year return period in Al Dhaid. (**b**) The increase in IDF curve values for a 10-year return period in Al Dhaid. (**c**) The increase in IDF curve values for a 100-year return period in Al Dhaid. (**d**,**e**) OLD and NEW IDF curve values for Al Dhaid, respectively.

The trend of increased rainfall intensity is not limited to shorter return periods, as evident in Figure 8b,c. These figures illustrate that rainfall intensity has increased for both 10-year and 100-year return periods, demonstrating a consistent upward shift in the IDF curve values. This suggests a sustained trend of increasing rainfall intensity across all return periods. For example, the rainfall intensity for a 10-year return period with a 30 min duration increased from 57.99 mm/h to 62.60 mm/h (a 7.9% rise), as shown in Figure 8b. This increase is even more pronounced for a 100-year return period with a 30 min duration, where the rainfall intensity surged from 115.98 mm/h to 139.99 mm/h (a 20.7% increase), as illustrated in Figure 8c.

Figure 8d,e provide a visual comparison of the OLD and NEW IDF curves for Al Dhaid, clearly illustrating the increase in rainfall intensity across various durations and return periods. This consistent upward trend in the curves underscores the shift towards more intense rainfall events.

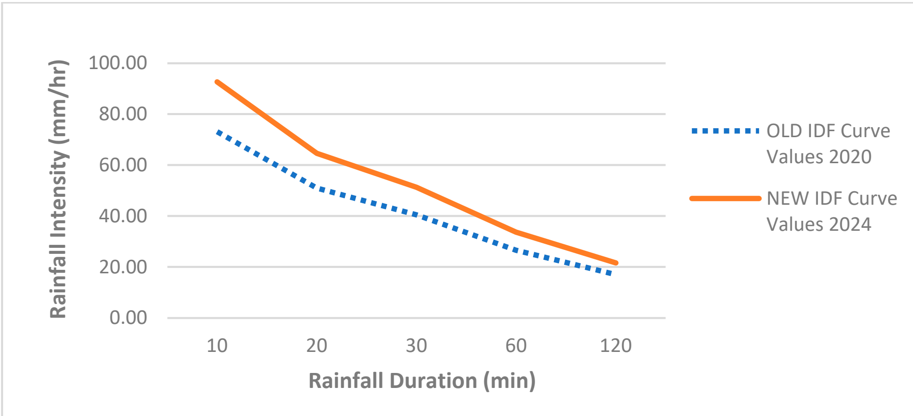
Figure 8e specifically presents updated IDF curves for Al Dhaid, confirming the trend of increasing rainfall intensity observed across the study area. These curves reveal a significant increase in rainfall intensity across a range of durations and return periods, particularly for shorter durations and lower return periods. This suggests a potential shift towards more frequent and intense rainfall events.

Comparing these findings to the results observed in Sharjah City, the pattern of increasing rainfall intensity across various durations and return periods appears to be a consistent trend across the entire study area, indicating a possible broader shift in rainfall patterns affecting the region.

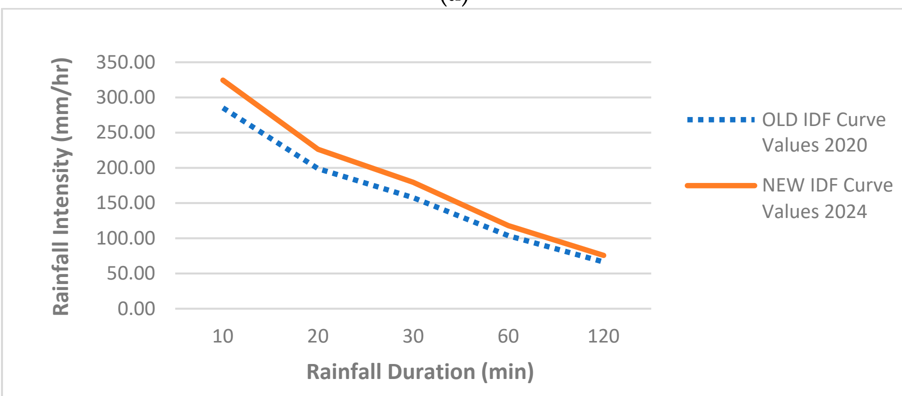
3.1.3. Mleiha

A comparison of IDF curve values between OLD and NEW records for Mleiha reveals a significant increase in rainfall intensities across all durations and return periods. However, the percentage increase is relatively lower than in the other two stations, likely due to Mleiha's initially higher rainfall records. Figure 9a presents the increase in IDF curve values for a 2-year return period. A clear upward shift in the intensity–duration curve is observed, indicating a notable increase in rainfall intensity. For example, the 10 min duration increased from 73.10 mm/h to 92.66 mm/h, representing a 26.7% rise, while the 60 min duration increased from 26.55 mm/h to 33.65 mm/h, showing a 26.7% rise. This suggests that Mleiha is experiencing more intense rainfall events even for shorter durations, and this trend needs to be considered in urban planning and flood management.

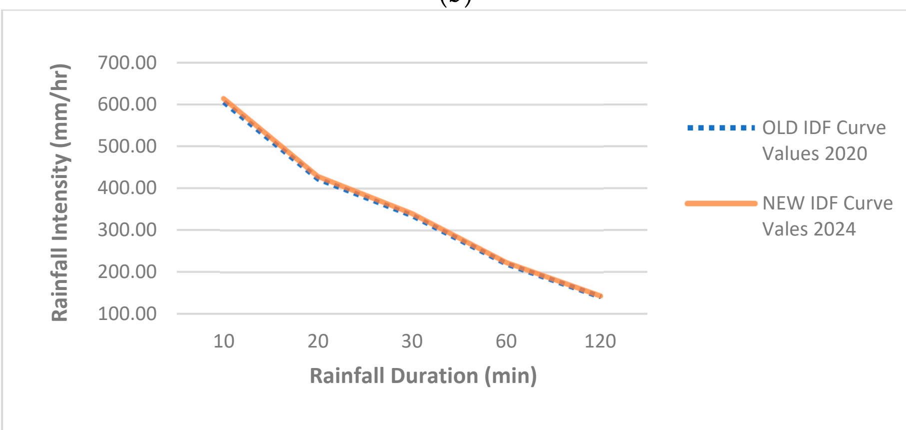
Figure 9b illustrates the increase in IDF curve values for a 10-year return period. Similar to Figure 9a, a clear upward shift in the curve is observed, indicating a continued increase in rainfall intensity. For instance, the 30 min duration for a 10-year return period increased from 157.77 mm/h to 179.57 mm/h, representing a 13.8% rise. Figure 9c further reinforces this trend, showcasing the increase in IDF curve values for a 100-year return period. Even for this longest return period, the curve displays a consistent upward shift, demonstrating that the trend of increased rainfall intensity is not limited to shorter return periods but extends to longer ones as well. While the increase for the 30 min duration is less pronounced at 1.3% (from 335.40 mm/h to 339.62 mm/h), it reinforces the overall pattern of rising intensity.



(**a**)

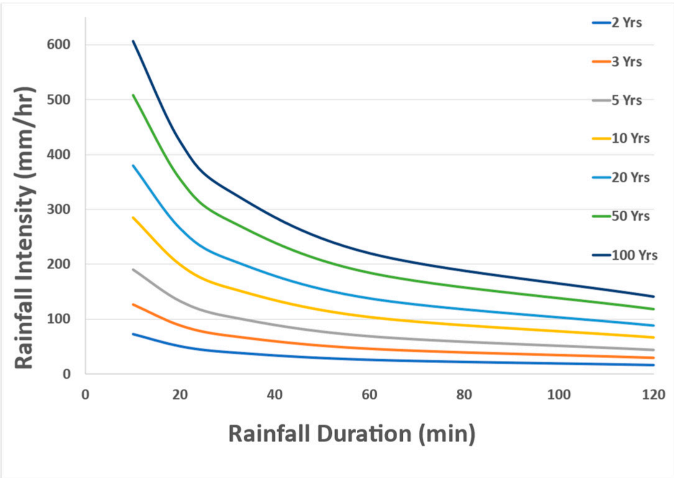


(**b**)

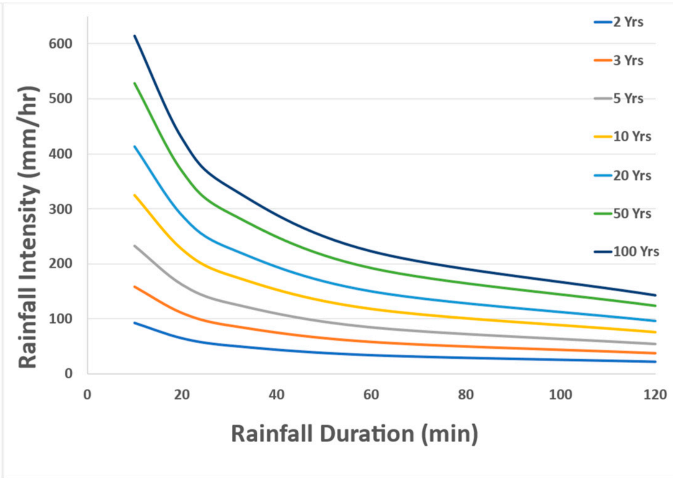


(**c**)

Figure 9. *Cont.*



(**d**)



(**e**)

Figure 9. (**a**) The increase in IDF curve values for a 2-year return period in Mleiha. (**b**) The increase in IDF curve values for a 10-year return period in Mleiha. (**c**) The increase in IDF curve values for a 100-year return period in Mleiha. (**d**,**e**) OLD and NEW IDF curve values for Mleiha, respectively.

An analysis of IDF curves for Mleiha reveals a clear trend towards more intense rainfall events, evident across all return periods. This upward trend in rainfall intensity is visually illustrated in Figure 9d,e, which compare the OLD and NEW IDF curves for the area. These figures clearly demonstrate the increasing intensity across a range of durations and return periods.

While the trend towards more intense rainfall events in Mleiha is less pronounced than the significant increases observed in Sharjah City and Al Dhaid, an analysis of IDF curves for Mleiha does reveal a clear upward trend in rainfall intensity across all return periods. This trend, though less dramatic than in the other two cities, is nonetheless notable, indicating a shift towards more frequent and intense rainfall events. This is reflected in the updated IDF curves for Mleiha, which show a clear increase in intensity across a range of durations and return periods.

3.2. Comparative Insights on Rainfall Variability in the Region: A Focus on the Sharjah Emirate

Understanding the changing patterns of rainfall is critical for effective water management and infrastructure planning in arid regions. This section delves into the intricacies of rainfall variability in the region by comparing findings from this study, which focuses on the recent intensification of rainfall in the Sharjah Emirate, with two studies examining longer-term rainfall patterns in neighboring Qatar. This comparative analysis reveals both commonalities and distinct perspectives, highlighting the complexities of rainfall variability in this region and the importance of considering both short-term and long-term trends when developing solutions for a changing climate.

The current study analyzed recent rainfall data from 2021 to April 2024, integrated with historical records spanning from 1992 to 2020. This research revealed a notable increase in rainfall intensities, with average increases of 36.76% in Sharjah, 26.52% in Al Dhaid, and 17.55% in Mleiha across various durations and return periods. These findings indicate a concerning trend towards more intense and frequent rainfall events, highlighting the urgent need for updates in hydrological models and infrastructure designs to bolster flood resilience.

In contrast, Mamoon and Rahman [18] examined rainfall patterns in Qatar over a longer timeframe, specifically from 1962 to 2010. Their research identified mixed trends across different monitoring stations. While some areas in the northern and eastern regions showed increasing rainfall, others, particularly in the southern and western regions, experienced declines or persistent dry conditions. This spatial variability underscores the importance of localized assessments for effective water resource management.

Furthermore, Mamoon and Rahman [19], in a second study, focused on determining the best-fit probability distributions for rainfall frequency analysis, covering the years from 1972 to 2010. They concluded that the Generalized Extreme Value (GEV) distribution was most suitable for the majority of monitoring stations. They emphasized the necessity of utilizing extended datasets to achieve accurate rainfall quantile estimates, especially for higher return periods. This reinforces the critical need for ongoing data collection to enhance the predictability and management of extreme weather events in arid regions.

This Sharjah Emirate study stands out for its focus on the rapid and urgent rise in rainfall intensity over a relatively shorter timeframe. This rapid change, potentially driven by climate change influences, highlights the immediate need for adaptation in infrastructure and hydrological models. However, the studies from Qatar provide a broader perspective, demonstrating both increases and decreases in rainfall across various regions over a longer timescale. This broader temporal variability may mask underlying long-term climate trends when viewed collectively.

While this Sharjah study emphasizes immediate adaptations in local infrastructure to address rapid shifts in weather patterns, the Qatar studies advocate for a nuanced understanding of rainfall variability that considers spatial differences and long-term trends. Taken together, these studies underscore the critical necessity of updating IDF curves regionally to accurately reflect changing precipitation patterns.

Ultimately, this comparative analysis emphasizes the urgency and complexity involved in understanding rainfall variability in arid regions. While the increasing intensity of rainfall in the Sharjah Emirate necessitates prompt action, the insights derived from Qatar's extensive studies provide valuable guidance on considering spatial differences and the importance of robust statistical methods for long-term planning. By incorporating these diverse perspectives, it is possible to develop more effective strategies for water resource management and infrastructure planning in the face of an evolving climate.

3.3. Impact of Climate Change on Rainfall Patterns in the Region

Recent results in Sharjah City, Al Dhaid, and Mleiha (UAE) have identified a concerning trend: an increase in rainfall intensity across various durations and return periods. This trend suggests that more intense and frequent rainfall events are becoming likely, driven by natural climate variability and anthropogenic climate change. The findings emphasize the urgent need for a comprehensive understanding of how climate change is reshaping rainfall patterns in the region.

These trends observed in the UAE are echoed in neighboring countries. In Qatar, studies indicate similar shifts towards unpredictable and intense rainfall, underscoring that these changes are indicative of broader climatic trends across the Arabian Peninsula and highlight shared vulnerabilities to climate impacts [20].

Research in Oman also emphasizes the effects of climate change on rainfall patterns. Studies have shown that rainfall intensities vary significantly across regions, with mountainous areas experiencing higher rainfall than coastal or desert regions. This indicates the importance of considering topographical influences in rainfall assessments [21]. Additionally, in Iran, Modabbermm-Azizi et al. [17] provide further context, illustrating notable variability in precipitation patterns largely driven by long-term climatic oscillations. While cloud seeding has impacted rainfall patterns in the UAE, recent drastic shifts indicate a more significant influence of climate change.

The implications of these findings are substantial for the countries in the region. Increasing rainfall intensity raises the risk of urban flooding, potentially overwhelming drainage systems and jeopardizing infrastructure, transportation networks, and public safety. Additionally, changes in the timing and frequency of rainfall complicate water resource management, increasing the risk of drought during dry spells and threatening agricultural productivity and water supplies.

These challenges necessitate updated IDF curves to reflect evolving climatic realities. Regular updates are essential for accurate flood risk assessments and for designing resilient infrastructure. It is recommended that updates occur at least every five years, supported by systematic rainfall data monitoring and advanced analytical techniques.

By prioritizing the update of IDF curves and understanding localized findings, cities in the region can enhance their resilience to the challenges of climate change. The insights from these studies provide a crucial foundation for strategic adaptation and planning in an era marked by increased climatic variability.

3.4. Implications and Recommendations

The analysis of rainfall data from January 2021 to April 2024, encompassing recent storm events, has revealed a significant increase in IDF curve values across Sharjah City, Al Dhaid, and Mleiha. This increase is evident across all durations and return periods, with particularly notable rises observed in shorter durations and lower return periods. For instance, Sharjah City has experienced a 39.3% increase in rainfall intensity for a 10 min duration at a 2-year return period. Similar trends are present in Al Dhaid and Mleiha, demonstrating a consistent pattern throughout the study area.

These findings emphasize the critical necessity to update IDF curves on both national and regional levels. The observed increase in rainfall intensity indicates more frequent and severe precipitation events, highlighting the need for revised hydrological models and updated infrastructure designs. Incorporating the revised IDF values is crucial for improving urban drainage systems, flood management strategies, and overall infrastructure resilience. This update will ensure better alignment with current and future precipitation patterns, thereby supporting sustainable development amid rising climatic variability.

This research significantly advances the field by integrating recent data to refine the assessment of rainfall intensity and frequency in arid regions, addressing a critical gap in understanding precipitation variability. By identifying substantial increases in IDF values and their implications for infrastructure and flood management, this study provides valuable insights into the impact of recent climatic changes on IDF curves. The detailed findings offer a comprehensive perspective for policymakers, urban planners, and researchers and present a methodology for updating IDF values with recent data and comparing them with historical records. This approach not only serves as a model for similar studies in arid climates but also significantly advances local flood risk management. The insights gained are applicable to other arid regions facing similar climatic challenges, highlighting the importance of developing effective adaptation strategies and improving infrastructure planning in the face of a changing climate.

4. Conclusions

The April 2024 rainfall events in the UAE have exposed critical vulnerabilities in the country's infrastructure and urban planning strategies. Despite advances in meteorological monitoring and predictive capabilities, the unprecedented intensity and duration of the rainfall revealed significant deficiencies in managing and mitigating urban flooding. The extensive submersion of residential properties, persistent road blockages, and the reactivation of long-dormant wadis highlight the urgent need for a thorough reassessment of current flood management practices.

This study, utilizing recent rainfall data, updated the IDF curves for the Sharjah Emirate, revealing a marked increase in rainfall intensities across all durations and return periods. Specifically, Sharjah showed an average increase of 36.76%, Al Dhaid experienced a 26.52% rise, and Mleiha had a 17.55% increase. These increases reflect a trend towards more severe and frequent rainfall events, influenced by both natural climatic changes and human activities such as cloud seeding.

The updated IDF values underscore the necessity for immediate revisions to the UAE's IDF curves used in urban drainage system designs. Accurate and up-to-date IDF curves are essential for developing infrastructure that can withstand both current and future extreme weather events. However, addressing these challenges goes beyond updating IDF curves. It requires a comprehensive evaluation of urban planning practices, hydrological infrastructure, flood preparedness, crisis management strategies, and global climatic coordination. Additionally, integrating advanced forecasting methodologies is crucial.

In conclusion, while updating IDF curves is critical, it must be part of a broader strategy that includes enhanced data collection, improved hydrological modeling, and a coordinated approach to flood management. Implementing these measures will strengthen the resilience of UAE cities, better protect communities and infrastructure, and ensure preparedness for future extreme weather challenges.

Author Contributions: Conceptualization, R.R. and K.B.A.; methodology, R.R. and K.B.A.; software, K.B.A.; validation, R.R.; formal analysis, K.B.A.; investigation, K.B.A.; resources, K.B.A.; data curation, K.B.A.; writing—original draft, K.B.A.; writing—review and editing, R.R., G.W. and A.J.A.; visualization, R.R.; supervision, R.R., G.W. and A.J.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data could be requested from the first author.

Acknowledgments: We sincerely thank the National Center of Meteorology in the UAE for their prompt response and ongoing support in providing updated meteorological records for the stations utilized in this study. We are particularly grateful to HE Abdullah Al Mandous, Director of the Center, and his dedicated team for their outstanding support in all meteorological and research-related matters. Additionally, we would like to express our gratitude to Eng. Anwaar Alshimmari, Executive Director of the Geospatial Governance Sector at the Federal Geographic Information Center in the UAE, for consistently providing valuable data on the tangible impact of the flooding discussed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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