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Impact assessment of climate change on rainfall Intensity Duration Frequency curve -Swat district, Khyber Pakhtunkhwa

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Abstract

When planning and constructing water infrastructure, rainfall intensity-duration-frequency (IDF) curves are frequently utilized in design of culverts, storm drains, and flood barriers etc. However, increased greenhouse gas emissions are causing climate change, which influences the frequency, length, and severity of rainfall episodes. Reducing the risk of urban flooding requires adaptation to these changes. IDF curves are essential resources for catering these variables ensuring water infrastructure is economical and safe. Thus, the IDF curve in this study was developed incorporating climate projections for Swat district of Khyber Pakhtunkhwa. The rainfall projection data spans ten years from 2024–2034 under (Shared Socioeconomic Pathways) SSP2-4.5. Using Gumbel distribution method the IDF curve is developed. The results of the study indicate that longer-duration rainfall episodes are less common and less severe over short return periods, under the assessed climate scenario. Rainfall intensity dramatically rises for the return period length 50, 75, and 100 years. Notably, rainfall intensity is marginally higher and more frequent for the 5-year and 10-year return periods. In order to successfully handle future flood risks, these trends can be taken into account while planning and developing water infrastructure for the Swat region.

Keywords: Climate change; Shared Socioeconomic Pathways (SSP); IDF curve; Rainfall intensity; Khyber Pakhtunkhwa (KP)

1. Introduction

Since 1970, the rate of increase in the global surface temperature has been higher than it has been for at least the last 2000 years in any prior 50-year period. The temperatures of the latest recent multi-century warm episode, which happened roughly 6500 years ago, are lower than those of the most recent decade (2011–2020) [0.2°C to 1°C above 1850–1900] [1]. Certainly, human activity contributed to global warming, with the global surface temperature rising by 1.1°C between 2011 and 2020, primarily due to greenhouse gas emissions. Global warming will increase as long as greenhouse gas emissions are sustained; modeled pathways and studied climate scenarios indicate that 1.5°C will be reached in the near future [2].

With a possible rise of 1.3°C–4.9°C by the 2090s over the 1986–2005 baseline, Pakistan is experiencing rates of warming that are significantly higher than the global average. Although it is extremely unlikely that Pakistan's rainfall and runoff patterns would change, there is a good chance that the frequency of drought conditions will rise. Pakistan's historical precipitation profile is complicated. Annual rainfall declined for a considerable amount of time in the early 20th century, however after 1960, there has been a minor increase in the trend [3]. The severity of Pakistan's climate problem is highlighted in the Intergovernmental Panel Climate assessment report 2021, which states that given the country's present climatic consequences, the glaciers might entirely melt, and freshwater supplies could run out by 2050 according to Global Climate Risk Index report 2021. Historically northern provinces are most affected by floods when

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heavy summer monsoon rainfall and glacial melt trigger flooding in the upper tributaries of the Indus basin [4]. For instance, in 1992, 1995, 2012, and 2021, northern provinces were severely affected, while in 2003, 2009, 2007, and 2020, southern provinces were worst hit by floods [5].

An unpredictable hydrological cycle brought on by climate change and human activity has resulted in both heavy rainfall events and droughts, severely disrupting lifestyles and businesses [6].There is risk of possibility of flooding mainly pluvial in highly populated urban regions of developed regions across the world due to immense increase of rainfall intensities concentrated for certain duration [7].

Rain is one of the important source that feeds the fresh water resources on Earth, provided by the long hydrological cycle; however, it can also be a source of natural disasters, such as urban flash floods [8].One major problem with IDF curves is they assume that the historical rainfall used to create the curves is stationary (i.e., not changing with respect to time).However, the factor of climate change is usually ignored that significantly impacts the hydrological cycle and rainfall patterns [9].Considering the impact of climate change ,rainfall intensity varies that is translated to IDF curves .Thus if climate change impact are ignored this will lead to under or overestimate of water resources related projects [10] .

In many hydrologic design projects, including drainage design, determining the rainfall event is one of the initial phases. strength-duration-frequency curves (IDF), which simultaneously display the strength and duration of a design storm, are typically used for this procedure. In the field of water resources engineering and management, intensity-duration-frequency (IDF) curves are among the most widely used tools for organizing, designing, and carrying out a variety of projects pertaining to water resources [11]. Consequently, a major challenge emerges for most countries and regions of the world to develop IDF curve under the assumption of climate change [9]. In the wake of the 2022 floods impact, this study assesses and explores the impact of climate change on rainfall duration and intensity. The data used for climate projections is derived from Shared Socio-economic Pathways, or 'SSP'. The most recent re-establishment of what if, scenarios that are used to investigate the effects of greenhouse gas concentration in the aerosphere and are called SSPs. SSP scenario 2-4.5(which projects greenhouse gas emissions to be moderate) is employed in the study for following objective; for effective water resources management to develop IDF curves assuming climate change impacts for district Swat of Khyber Pakhtunkhwa, Pakistan.

This study utilizes climate projections data to develop IDF curves for most flood impacted region in KP province, Swat and to propose future water management infrastructure design solutions that is employed in water resources planning and flood risk management. The methodology is as detailed in section 2.

2. Material and methods

2.1. Study area and Data Collection

Figure 1 Map of Swat region, Source Google Earth

The study is conducted for the region Swat of Khyber Pakhtunkhwa province of Pakistan due t its susceptibility to major flood events that is in 2010 and in 2022 [12] followed by many minor scale flood hazards . It is located in 34.8065° N, 72.3548° E.

In this study the IDF curve is developed from climate projections data from 10 years that is 2024-2034 rainfall pattern. The climate projections data is obtained from Coupled Model Intercomparison Project Phase 6 CMIP6 database under SSP2-4.5. The regional meteorological (rainfall) data is analyzed in MATLAB followed by applying empirical methods in MS Excel to determine and develop IDF chart based on the regional future climate projections.

2.2. IDF Curve Development

For development of IDF curve the maximum rainfall data from 2024-2034 is employed which are employed as variable in the empirical formulas using Gumbel distribution method.

2.3. Gumbel Distribution

The Gumbel method was established by the German mathematician Emil Gumbel and has been widely used for modeling extreme events in hydrology and other fields [13]. A book by Kotz and A. Nadarajah [14] describes this distribution and cites more than 50 applications, including earthquakes, floods, horse racing, rainfall, supermarket lines, sea currents, wind speeds, track race records, and accelerated life tests. Since this approach has emerged as the most popular distribution for IDF, it was selected to carry out the flood probability study [15]. The Gumbel method is a straightforward and easy-to-use technique that can be used in severe situations (peak rainfalls or maximum values), as noted by [16].The following empirical formulas are implied in the creation of the IDF curve:

$$X_T = \bar{X} + K.\sigma_x \qquad \text{Eq (1)}$$

$$K = \frac{Yt - \overline{Yn}}{Snx} \qquad \text{Eq (2)}$$

$$Y_T = \text{Reduced Variate, } Y_T = -\,[\text{Ln. Ln. } (\tfrac{T}{T-1})] \qquad \text{Eq (3)}$$

Where X_T is the total rainfall from mean and S.D , X = mean rainfall , σx = Standard deviation of the Sample Size ,K_T = Frequency Factor, which is expressed as shown in Eq (2).The values of and Sn are selected from Gumbel's Extreme Value Distribution considered depending on the sample size as shown in Figure 2. The values of Y_T and K_T employed in this study are shown in Table 1 that is used for various return periods.

Table 1 Gumbel distribution factor used for IDF curve development for Swat, KP

Time Period (year)	2	5	10	50	75	100
Y_T	0.3665129	1.49994	2.250367	3.90194	4.31078	4.60015
K_T	-0.135517	1.058067	1.848323	3.58755	4.0181	4.32282

TABLE –1 – REDUCED MEAN $\bar{y}_n$ IN GUMBEL'S EXTREME VALUE DISTRIBUTION

N = sample size

N	0	1	2	3	4	5	6	7	8	9
10	0.4952	0.4996	0.5035	0.5070	0.5100	0.5128	0.5157	0.5181	0.5202	0.5220
20	0.5236	0.5252	0.5268	0.5283	0.5296	0.5309	0.5320	0.5332	0.5343	0.5353
30	0.5362	0.5371	0.5380	0.5388	0.5396	0.5402	0.5410	0.5418	0.5424	0.5430
40	0.5436	0.5442	0.5448	0.5453	0.5458	0.5463	0.5468	0.5473	0.5477	0.5481
50	0.5485	0.5489	0.5493	0.5497	0.5501	0.5504	0.5508	0.5511	0.5515	0.5518
60	0.5521	0.5524	0.5527	0.5530	0.5533	0.5535	0.5538	0.5540	0.5543	0.5545
70	0.5548	0.5550	0.5552	0.5555	0.5557	0.5559	0.5561	0.5563	0.5565	0.5567
80	0.5569	0.5570	0.5572	0.5574	0.5576	0.5578	0.5580	0.5581	0.5583	0.5585
90	0.5586	0.5587	0.5589	0.5591	0.5592	0.5593	0.5595	0.5596	0.5598	0.5599
100	0.5600									

TABLE –2 – REDUCED STANDARD DEVIATION S_n IN GUMBEL'S EXTREME VALUE DISTRIBUTION

N = sample size

N	0	1	2	3	4	5	6	7	8	9
10	0.9496	0.9676	0.9833	0.9971	1.0095	1.0206	1.0316	1.0411	1.0493	1.0565
20	1.0628	1.0696	1.0754	1.0811	1.0864	1.0915	1.0961	1.1004	1.1047	1.1086
30	1.1124	1.1159	1.1193	1.1226	1.1255	1.1285	1.1313	1.1339	1.1363	1.1388
40	1.1413	1.1436	1.1458	1.1480	1.1499	1.1519	1.1538	1.1557	1.1574	1.1590
50	1.1607	1.1623	1.1638	1.1658	1.1667	1.1681	1.1696	1.1708	1.1721	1.1734
60	1.1747	1.1759	1.1770	1.1782	1.1793	1.1803	1.1814	1.1824	1.1834	1.1844
70	1.1854	1.1863	1.1873	1.1881	1.1890	1.1898	1.1906	1.1915	1.1923	1.1930
80	1.1938	1.1945	1.1953	1.1959	1.1967	1.1973	1.1980	1.1987	1.1994	1.2001
90	1.2007	1.2013	1.2020	1.2026	1.2032	1.2038	1.2044	1.2049	1.2055	1.2060
100	1.2065									

Figure 2 Reduced mean and reduced standard deviation values for Gumbel Distribution method, Source; University of Mustansiriyah, n.d

3. Results and discussion

The IDF curves were developed from climate projections data as mentioned in section from 2024–2034-time frame analyzed from SSP2-4.5 model. The highest annual peak rainfall and day of peak rainfall is determined from MATLAB from the rainfall projections data for the mentioned time period. After this climate projected IDF curve is developed using Gumbel distribution formulae as mentioned in section 2. Using variables rainfall duration, rainfall intensity for the return period of 2 year,5 year,10 year,50 year ,75 year and 100 year. The graph obtained, however, is closely packed for which logarithmic graph type is used to have a clear understanding of IDF curve behavior under the future climate projections for the district Swat.

From the climate projections obtained from CMIP6 ,the rainfall data is filtered out for peak rainfall event which enabled to have a detailed insight into future rainfall highest annual daily peak result of which are shown in table along with the projected day of maximum rainfall event .The maximum daily rainfall event in mm is then converted to duration of certain minutes which is later employed in development of IDF curve using Gumbel distribution method .from the Table 1 it is to be noted that the daily peak annual rainfall moderately remains around 50-60 mm for the 10 years' time frame analyzed with exceptional rainfall peaks of 99 mm projected in 2025 followed by 78 mm in 2031 and the highest daily rainfall of 187 mm projected in 2032 .

Table 1 Climate projections maximum rainfall data set under SSP2-4.5 for Swat, KP

Rainfall in mm over time (minutes)										
Year	**Highest daily peak Annual (mm)**	**Date of Max Rainfall**	**5**	**10**	**15**	**30**	**60**	**120**	**720**	**1440**
2024	54.5	02/25/2024	8.3	10.4	11.9	15.0	18.9	23.8	43.3	54.5
2025	99	02/25/2025	15.0	18.9	21.6	27.2	34.3	43.2	78.6	99.0
2026	59	10/17/2026	8.9	11.3	12.9	16.2	20.5	25.8	46.8	59.0
2027	63	01/08/2027	9.5	12.0	13.8	17.3	21.8	27.5	50.0	63.0
2028	64.4	01/25/2028	9.8	12.3	14.1	17.7	22.3	28.1	51.1	64.4
2029	62	03/28/2029	9.4	11.8	13.5	17.1	21.5	27.1	49.2	62.0
2030	65	07/16/2030	9.8	12.4	14.2	17.9	22.5	28.4	51.6	65.0
2031	78	02/23/2031	11.8	14.9	17.0	21.5	27.0	34.1	61.9	78.0

2032	187	08/06/2032	28.3	35.7	40.8	51.5	64.8	81.7	148.4	187.0
2033	60.7	02/15/2033	9.2	11.6	13.3	16.7	21.0	26.5	48.2	60.7
2034	51	07/15/2034	7.7	9.7	11.1	14.0	17.7	22.3	40.5	51.0

Followed by data set organized for Gumbel distribution variables .IDF curve is developed using the mean and standard deviation of mentioned time duration in minutes from table against which reduced mean and reduced standard deviation (S.D)is determined as the time sets around ten years the vales are determined from this is followed by time duration conversion from daily to hourly basis starting with hour 0.0833 and integrating to 24 hour time .rainfall intensity in mm/hour using mean , standard deviation and frequency factor. The results of which are shown from IDF curve in Figure 1.

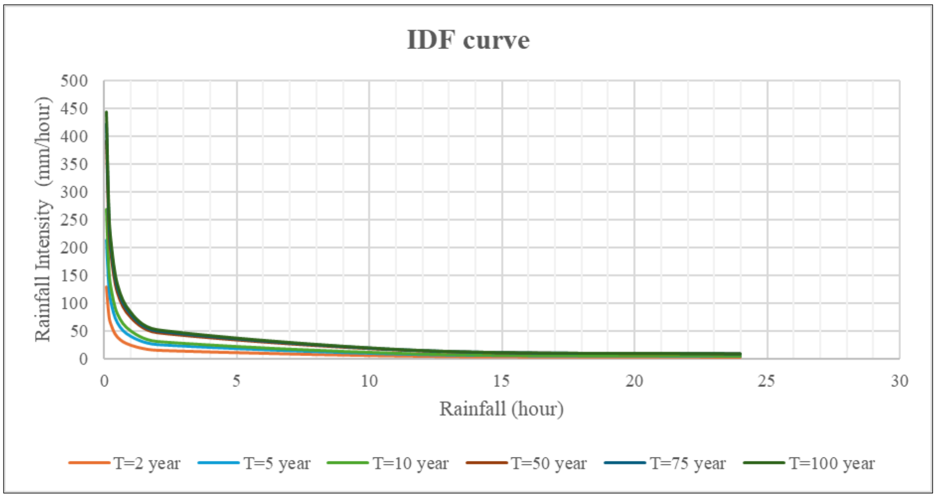

Figure 1 IDF Curve from climate projections under SSP2-4.5 from year 2024-2034 rainfall data set for different return periods

The development of IDF curve consists of variables on x-axis is the (daily)24-hour pattern of rainfall. Whereas y axis represents rainfall intensity. From the graph it can be seen that the return periods are closely packed with return periods of 2- and 5-year having rainfall intensity around 120 mm to around 200 mm. However, for the remining four return periods the logarithmic graph plot can be referenced. The Table 2 represents the variables employed for different time duration in minutes and rainfall intensities for a set of six return period that is 2 year development of IDF curve form climate projection scenario SSP2-4.5 for Swat district.

Table 2 Gumbel Distribution Calculated variables of Rainfall intensity and Duration for different return periods for Swat, KP

Return period (year)	**2**	**5**	**10**	**50**	**75**	**100**
Time (hour)	Rainfall Intensity (mm/hour)					
0.083333	129.8	214.0	269.8	392.5	422.9	444.4
0.166667	81.8	134.8	170.0	247.3	266.4	279.9
0.25	62.4	102.9	129.7	188.7	203.3	213.6
0.5	39.3	64.8	81.7	118.9	128.1	134.6
1	24.8	40.8	51.5	74.9	80.7	84.8
2	15.6	25.7	32.4	47.2	50.8	53.4
12	4.7	7.8	9.8	14.3	15.4	16.2
24	3.0	4.9	6.2	9.0	9.7	10.2

The log-log IDF curve graph shows a much-pronounced insight into the behavior of future rainfall pattern on IDF curve of Swat region. On x axis is the duration of rainfall in hours while on y axis is rainfall intensity in mm/hour. The graph shows that for the return period of 2 years the rainfall is the lowest with rainfall around 130mm. However, for the 5-year return period, the rainfall intensity grows exceptionally and is followed by rise for 10 year return period rainfall intensity. However, for 50 year ,75 year and 100 year return period the rainfall intensity is jampacked for a 24 hour rainfall period with exceptionally high peak events.

This indicates that the exceptional rainfall events span over longer periods and return period. The curve of 50,75- and 100-year return period indicates that rainfall intensity gradually increases as return year duration increases. However, for shorter return periods the rainfall intensity is around 50 to 70 mm/hour and is frequent in occurrence.

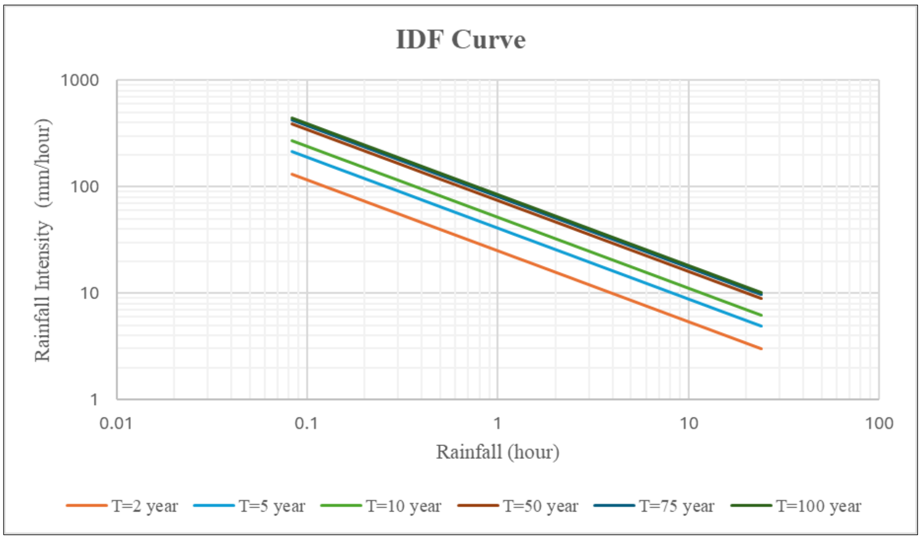

Figure 2 Log-log IDF Curve for different return periods for variables between rainfall duration and rainfall intensities under SSP2-4.5

4. Conclusion

The IDF development from climate projections data under the SSP scenario 2-4.5 for the region Swat, indicates that shorter return rainfall events are less intense and frequent for shorter duration return periods. As the return period duration extends to 50,75 and 100 years the rainfall intensity also exceptionally increases which is consistent with the idea that extreme rainfall events tend to rarely happen. However, it is the 5 year and 10-year return period, where the rainfall intensity slightly and is concentrated and frequent. Under the impacts of climate change assessed in this study, rainfall pattern for shorter return period is frequent which tells that in the near future that such rainfall events if concentrated in duration of daily basis in a week /month (and not spread along the length of year) might create problems which should be taken care of while designing water infrastructures for Swat region.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares no conflict of interest.

References

[1] Intergovernmental Panel On Climate Change (Ipcc), Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press, 2023. doi: 10.1017/9781009157896.

[2] K. Calvin et al., "IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee

and J. Romero (eds.)]. IPCC, Geneva, Switzerland.," Intergovernmental Panel on Climate Change (IPCC), Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[3] World Bank Group and Asian Development Bank, Climate Risk Country Profile: Pakistan. World Bank, 2021. doi: 10.1596/36372.

[4] J. S. Nanditha et al., "The Pakistan Flood of August 2022: Causes and Implications," Earth's Future, vol. 11, no. 3, p. e2022EF003230, 2023, doi: 10.1029/2022EF003230.

[5] G. Mahar and N. Zaigham, "The Impact of environmental changes on indigenous agriculture in the Indus Delta Pakistan: a spatio-temporal assessment," Arabian Journal of Geosciences, vol. 14, Feb. 2021, doi: 10.1007/s12517-021-06619-0.

[6] "Disruption in Earth's Water Cycle - Civilsdaily." Accessed: Sep. 04, 2024. [Online]. Available: https://www.civilsdaily.com/news/disruption-in-earths-water-cycle/

[7] C. Wasko, R. Nathan, L. Stein, and D. O'Shea, "Evidence of shorter more extreme rainfalls and increased flood variability under climate change," Journal of Hydrology, vol. 603, p. 126994, Dec. 2021, doi: 10.1016/j.jhydrol.2021.126994.

[8] N. S. Al-Amri and A. M. Subyani, "Generation of Rainfall Intensity Duration Frequency (IDF) Curves for Ungauged Sites in Arid Region," Earth Syst Environ, vol. 1, no. 1, p. 8, Jun. 2017, doi: 10.1007/s41748-017-0008-8.

[9] I. M. Kourtis and V. A. Tsihrintzis, "Update of intensity-duration-frequency (IDF) curves under climate change: a review," Water Supply, vol. 22, no. 5, pp. 4951–4974, May 2022, doi: 10.2166/ws.2022.152.

[10] C. Martinez, Y. G. Her, and E. Bean, "Accounting for Climate Change in Rainfall Intensity-Duration-Frequency (IDF) Curves for Stormwater Management: AE596, 1/2024," EDIS, vol. 2024, no. 1, Feb. 2024, doi: 10.32473/edis-ae596-2024.

[11] S. P. Simonovic, A. Schardong, D. Sandink, and R. Srivastav, "A web-based tool for the development of Intensity Duration Frequency curves under changing climate," Environmental Modelling & Software, vol. 81, pp. 136–153, Jul. 2016, doi: 10.1016/j.envsoft.2016.03.016.

[12] U. F. Zaidi, "WWF reports differences between 2010 and 2022 Floods," The Diplomatic Insight. Accessed: Sep. 09, 2024. [Online]. Available: https://thediplomaticinsight.com/wwf-reports-differences-between-2010-and-2022-floods/

[13] E. J. Gumbel, "The Return Period of Flood Flows," Ann. Math. Statist., vol. 12, no. 2, pp. 163–190, Jun. 1941, doi: 10.1214/aoms/1177731747.

[14] S. Kotz and S. Nadarajah, Extreme Value Distributions: Theory and Applications. PUBLISHED BY IMPERIAL COLLEGE PRESS AND DISTRIBUTED BY WORLD SCIENTIFIC PUBLISHING CO., 2000. doi: 10.1142/p191.

[15] M. T. Amin, M. Rizwan, and A. A. Alazba, "A best-fit probability distribution for the estimation of rainfall in northern regions of Pakistan," Open Life Sciences, vol. 11, no. 1, pp. 432–440, Jan. 2016, doi: 10.1515/biol-2016-0057.

[16] I. H. Elsebaie, "Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia," Journal of King Saud University - Engineering Sciences, vol. 24, no. 2, pp. 131–140, Jul. 2012, doi: 10.1016/j.jksues.2011.06.001.