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Precipitation Frequency Analysis for Hydraulic Structures Design in Sub-Basins of the Swat River Basin

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Abstract: This study undertakes a comprehensive precipitation frequency analysis for sub-basins in the Swat River Basin (SRB) in Pakistan with the objective of developing resilient hydraulic structures. The SRB is highly susceptible to extreme flooding due to its highly sloping topography, intense monsoon rainfall, and rising trends of climate variability. In this context, precipitation data from 1990 to 2014 and future projections under SSP2-4.5 scenario from 2025 to 2099 were considered. HEC-SSP software was used to analyze precipitation data. Various probability distributions, such as Normal, Log Normal, Log Pearson Type III, and Gumbel, were considered. Gumbel's Extreme Value Type-I Distribution is considered appropriate for precipitation analysis. The precipitation analysis yielded maximum 1-day precipitation estimates with return periods ranging from 5 to 1000 years for sub-basins in SRB. From the analysis, it is evident that precipitation extremes vary in space. Marghazar-Jambail and Barikot sub-basins are found to have the highest precipitation extremes, with rainfall intensities of over 340 mm for 1000-year return periods under SSP2-RCP 4.5 scenario. These findings indicate an upward trend in precipitation extremes under future conditions. This study provides critical, evidence-based input for the design of hydraulic structures in the Swat River Basin.
Keywords: Precipitation, Frequency Analysis, Subbasin, Hydraulic Structures, GCM

I. INTRODUCTION

Pakistan ranks in the top ten of the most climate-vulnerable countries, as documented by the Global Climate Risk Index. In this context, there has been a significant increase in flood events in the northern mountainous regions, including the Swat River Basin, due to variations in precipitation patterns, snowmelt, and the occurrence of Glacial Lake Outburst Floods. The high-altitude catchment area of the basin appears to play a significant role in hydrological responses and peak discharges, as well as supporting socio-economic lives of the people in the region. The Swat River Basin, a part of the northern mountainous regions of Pakistan, is highly susceptible to extreme flood events resulting from the combined effects of intense rainfall occurring during the monsoon season, snowmelt, and climate variability. In this context, this study aims to perform a precipitation frequency analysis for designing hydraulic structures, considering historical data from the years 1990-2014 and future climate conditions as projected by the SSP2-4.5 scenario.

These risks have been exacerbated over the years because of climate change. For instance, climate change has caused an increase in the melting of glaciers because of the rise in temperature. In addition, there has been an increase in precipitation and rapid surface runoff. This has caused an increase in flood peaks. The flood experienced in the Swat Basin in the years 2010 and 2022 is evidence that the risks in this region are on the higher side. The effects of the floods have been devastating. The effects have been severe in the rural areas and agricultural activities.

The hydrological risks in the Swat Basin are unpredictable. Therefore, it is important to come up with effective and sustainable flood management strategies in the region. The need for comprehensive hydrological investigations in the Swat Basin, with regard to precipitation frequency analysis in the Swat Basin, is important in the development of effective hydraulic structures. The results of the study will be important in decision-making in the development of hydraulic structures. The study also addresses the need for climate-resilient engineering.

II. BACKGROUND

Flooding is considered one of the most devastating natural disasters in the world, especially in mountainous regions where complex topography, susceptible geological conditions, and highly fluctuating climatic patterns often result in hydrological responses. The mountainous regions, characterized by steeper slopes, thin soils, and minimal flood storage, are often associated with rapid runoff and high flood discharges, especially during intense rainfall and snowmelt events. [1-3].

In the recent past, the number and degree of flooding in mountainous areas have been exacerbated by climate change and changes in land use and population growth in these areas. According to global assessments, the rise in extreme rainfall caused by climate change has significantly altered the flood regime in mountainous areas in Europe, Asia, and South America. [4].

Swat River Basin is located in the northern part of Khyber Pakhtunkhwa, Pakistan. The Swat River Basin is highly vulnerable to flash floods due to its steep topography, narrow river valleys, and increased rainfall patterns caused by climate change. [5].

The exposure of the Swat River Basin to monsoon rainfall, quick snowmelt, and probable glacial lake outburst floods (GLOFs) making it one of the most flood-vulnerable river systems in the Upper Indus region [6-7].

Hilly catchments are characterized by highly nonlinear hydrological responses, primarily due to significant elevation gradients, spatial variability of precipitation, and complex interactions of rainfall, snowmelt, and glacier melt processes. Orographic effects are important for the spatial distribution of precipitation and are often a dominant factor in generating localized extreme rainfall events that may lead to flash floods [8-9]. Research and technical reports by JICA indicate that the flood regime of the Swat River is characteristic of snow-fed systems, with summer discharges typically ranging from 10 to 12 times higher than those observed during winter [10].

Climate change has also manifested as a significant factor controlling hydrological variability in mountainous regions. The increase in temperature has led to a rise in the rate of evapotranspiration, altered precipitation patterns by converting snowfall into rainfall, and changed the timing and magnitude of runoff in hilly regions. According to climate model predictions, there will be a rise in the number of short duration, high-intensity rainfall events, which are most efficient in causing flash floods. [3].

Recent studies have shown that the projected climate change may increase flood hazard and peak river discharge in the Himalayan catchments. This shows a significant increase in flood magnitude for future Shared Socioeconomic Pathways, indicating the limitations of infrastructural measures designed based on historical data and the need for climate-resilient approaches in designing flood mitigation measures. [11].

The Swat River Basin, which drains a vast mountainous area in Khyber Pakhtunkhwa, is used for agricultural activities, medium and small-scale hydropower generation, water supply schemes, fish hatchery, and tourism. However, the Swat River Basin is often affected by recurrent flooding, especially during extreme monsoon events such as in 2010, 2022, and 2024[12-13]. Seasonal streamflow in high-altitude basins, such as the Swat River Basin, is mainly influenced by rainfall and snowmelt. Although the rate of glacier melting has increased in the region, the contribution of glaciers to streamflow is small. Therefore, peak flows in the basin are mainly influenced by rainfall and snowmelt. [14].

The effects of floods in the Swat Basin are worsened by rapid urbanization, deforestation, encroachment, and improper land use planning. Studies suggest that these activities have greatly increased runoff coefficients and decreased the natural flood storage capacity of the basin. Thus, the exposure and vulnerability of people living in these areas, especially in downstream areas, have greatly increased. These areas of ignorance and management provide an opportunity for further research in hydrology, especially in modelling flood processes, improving land use planning, and developing effective flood mitigation measures, in which the main step in flood hydrology is precipitation frequency analysis.

III.METHODOLOGY AND STUDY AREA

The Swat River Basin is in northern Khyber Pakhtunkhwa, Pakistan, with mountainous catchment areas having steep slopes, followed by gentle valleys in the lower catchment area. The river basin displays complex hydrological processes due to rocky terrain, significant spatial variability in precipitation, and high runoff.

The river basin in this study was divided into 18 sub-basins, as shown in **Figure 1,** contributing to the main river, for which precipitation frequency analysis was carried out.

Rainfall Frequency Analysis was performed using HEC-SSP software to estimate the maximum 1-day precipitation values for different return periods. Various probability distribution curves, such as Normal Distribution, Log Normal Distribution, Log Pearson Type III Distribution, and Gumbel Distribution, were considered and compared. The Gumbel Extreme Value Type-I Distribution is finally considered suitable to estimate precipitation values under historical and SSP2-4.5 scenarios.

As presented in the flowchart in **Fig. 2**, the systematic approach for rainfall frequency analysis is carried out through the HEC-SSP software. The approach is mainly aimed at determining the maximum 1-day precipitation for specific return periods. The approach commences with the selection of probability distributions. Probability distributions are statistical models that describe the nature and behavior of rainfall events. In this study, rainfall events are considered through four different distributions, namely Normal, Log-Normal, Log-Pearson Type III, and Gumbel. These are frameworks for analysis of rainfall events and for understanding the possibilities of rainfall events occurring within a specific time period.

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Once the distributions are set up, the process of goodness of fit analysis and comparison with regional studies begins. This process helps in validating the appropriateness of the chosen distribution in a way that not only does it match the rainfall data statistically, but it also matches the results that have been obtained from previous studies within the region.

Following this process of evaluation, two scenarios emerge for the analysis: Historical Conditions and the SSP2-4.5 Scenario. The analysis of the historical conditions relies on the rainfall data accumulated from previous records to determine the extremes of rainfall, whereas the analysis of the SSP2-4.5 scenario takes into consideration the effects of climate changes that might be experienced in the future due to an increase in greenhouse gases. These two scenarios enable the analysis to look forward to the changes that might be experienced in extreme rainfall in the future.

Finally, on the basis of the goodness of fit, the Gumbel extreme value type I distribution is chosen to estimate the design precipitation. This is because it can be used to estimate extreme value type I, which can be used to model maximum daily rainfall. This type of extreme value type I distribution is commonly used for designing various structures in water resources engineering.

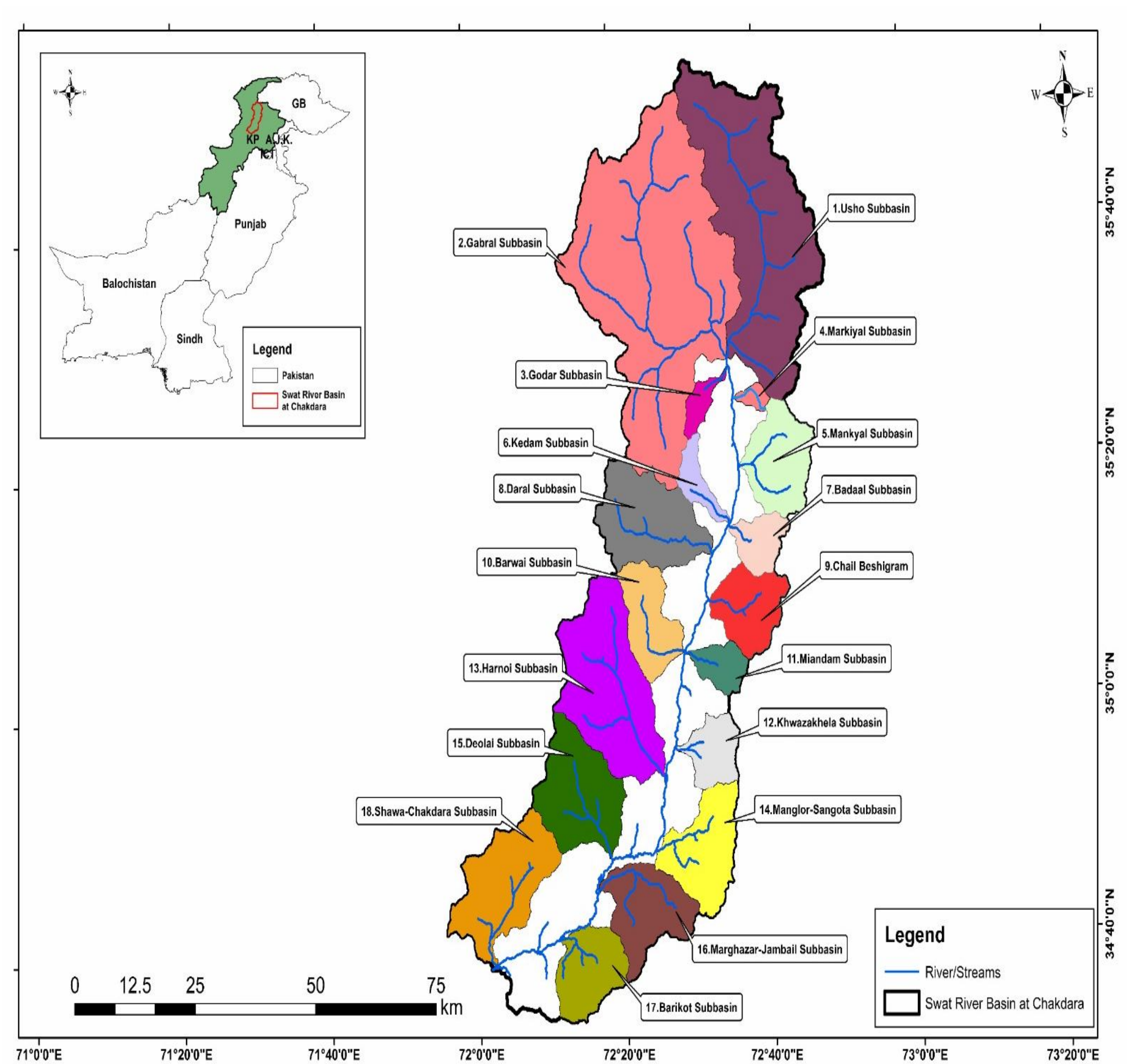

Fig. 1 Study Area

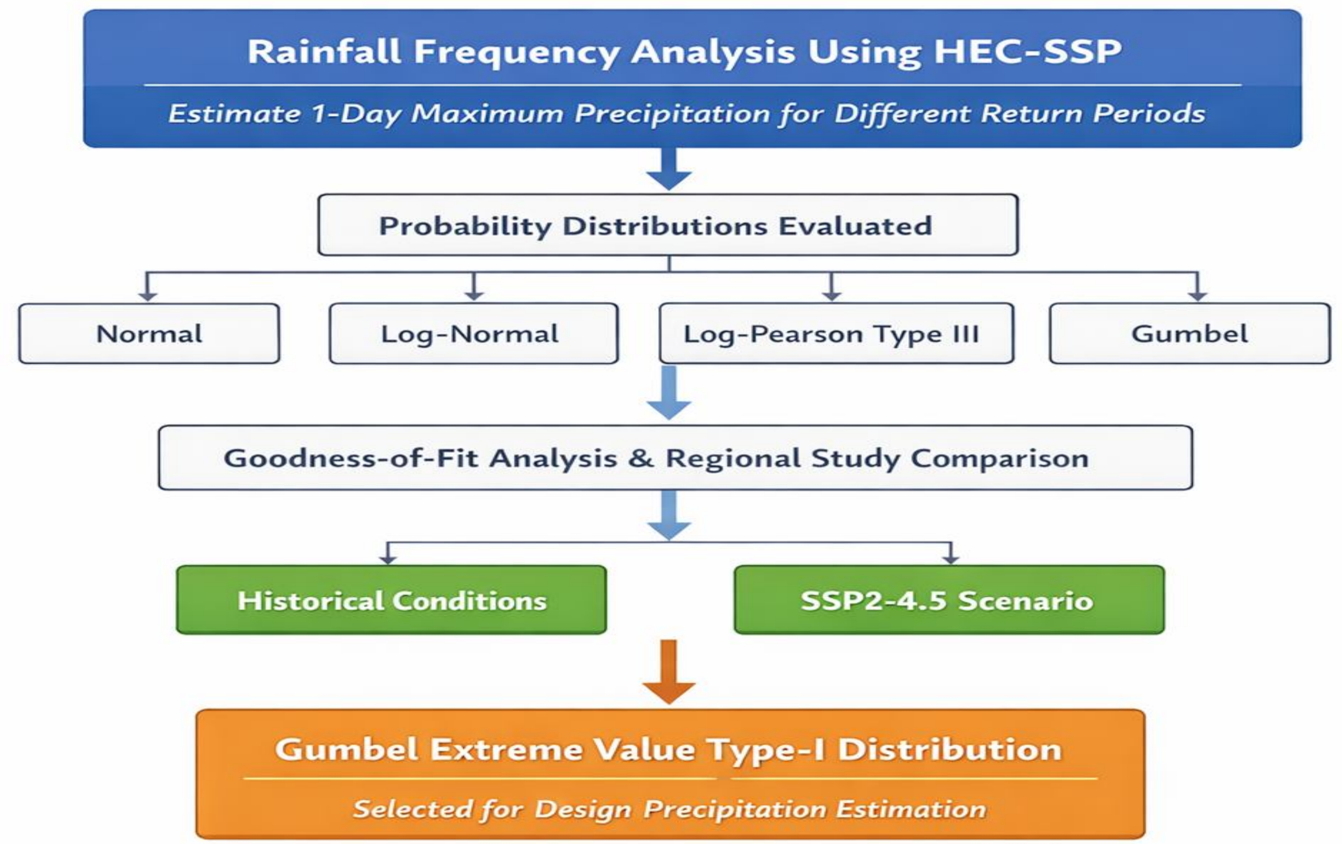

Fig. 2 Rainfall Frequency Analysis methodology

IV. RESULTS AND DISCUSSIONS

The objective of the study is to investigate precipitation patterns in the Swat River Basin by assessing precipitation characteristics in eighteen sub-basins of the catchment area, namely Usho, Gabral, Godar, Markiyal, Mankyal, Kedam, Badaal, Daral, Chail Beshigram, Barwai, Miandam, Khwazakhela, Harnoi, Manglor-Sangota, Deolai, Marghazar-Jambail, Barikot, and Shawa-Chakdara. The historical precipitation data set from 1990 to 2014 is used to estimate the precipitation extremes in the form of maximum 1-day rainfall with return periods of 5 to 1000 years.

Results indicate significant spatial variability in precipitation characteristics in the catchment area, mainly influenced by altitude and orographic effects. It is observed that under historical conditions, higher precipitation values are recorded in the Chail Beshigram sub-basin area for shorter return periods, whereas in the Marghazar-Jambail sub-basin area, higher rainfall values are recorded for longer return periods. The results show that extreme rainfall values increase with increasing return periods, indicating heterogeneous precipitation characteristics in the catchment area. Such results are of significant importance in flood risk assessment in sub-basins of the catchment area.

Results of future precipitation scenarios show that precipitation values are expected to rise in the catchment area between 2025 and 2099 under the SSP2-4.5 scenario. At shorter return periods, the Marghazar-Jambail sub-basin area is expected to record relatively higher rainfall values compared to other sub-basins in the catchment area. However, in the case of longer return periods, the Manglor-Sangota, Marghazar-Jambail, and Barikot sub-basins are expected to record higher precipitation values, indicating higher susceptibility to extreme rainfall events in these sub-basins. On the other hand, in the Usho, Gabral, and

The increase in precipitation extremes in all sub-basins with an increase in return periods is evident. This is an indication of the importance of considering climate change projections in hydrological analysis. These findings are of significant importance in hydraulic structure design. In conventional hydraulic structure design, only past data are considered. However, in this case, by considering precipitation projections, it is possible to precisely estimate runoff and flood peaks. This can lead to stronger hydraulic structures under future climatic conditions.

Analysis of sub-basins is also of great importance in efficient and precise planning. In some areas with higher rainfall intensity, such as Manglor-Sangota, Marghazar-Jambail, and Barikot, stronger hydraulic structure considerations are required. In contrast, in some sub-basins with relatively lower precipitation intensity, such as Usho, Gabral, and Godar, it is possible to consider lower return periods depending on the importance of hydraulic structures.

This sub-basin analysis is of great importance in precisely estimating flood risks and hydrological response analysis. In addition, it is possible to develop localized flood management strategies with the inclusion of precipitation extremes in both high-altitude and low-lying areas. More detailed findings are shown in Tables 1 and 2 and Figures 3 and 4.

Table 1. Subbasin wise Precipitation Frequency Analysis (Historic Data)

S #	Subbasins	Precipitation (mm) Historical 1990-2014							
		Return Periods (yr)							
	Return Year Period (yr)	5	10	50	100	150	200	500	1000
1	Usho Subbasin	49	68	110	128	138	146	169	187
2	Gabral Subbasin	50	69	113	131	142	149	173	191
3	Godar Subbasin	57	80	130	151	163	172	199	220
4	Markiyal Subbasin	70	97	158	183	198	209	242	268
5	Mankyal Subbasin	69	97	157	182	197	208	241	266
6	Kedam Subbasin	66	93	151	176	190	200	233	257
7	Badaal Subbasin	73	102	165	192	208	219	254	281
8	Daral Subbasin	62	87	142	165	179	189	219	242
9	Chail Beshigram	97	112	131	145	159	167	191	205
10	Barwai Subbasin	62	87	141	165	178	188	218	241
11	Miandam Subbasin	73	103	168	195	211	223	259	286
12	Khwazakhela Subbasin	76	108	176	205	222	234	272	301
13	Harnoi Subbasin	65	92	151	176	190	201	234	258
14	Manglor-Sangota Subbasin	78	110	180	209	226	239	278	307
15	Deolai Subbasin	71	101	165	193	209	220	256	283
16	Marghazar-Jambail Subbasin	82	116	190	222	240	253	294	326
17	Barikot Subbasin	76	108	177	207	224	236	275	304
18	Shawa-Chakdara Subbasin	78	111	183	214	232	244	284	315
19	Swat River Basin at Chakdara	56	79	129	150	163	171	199	220

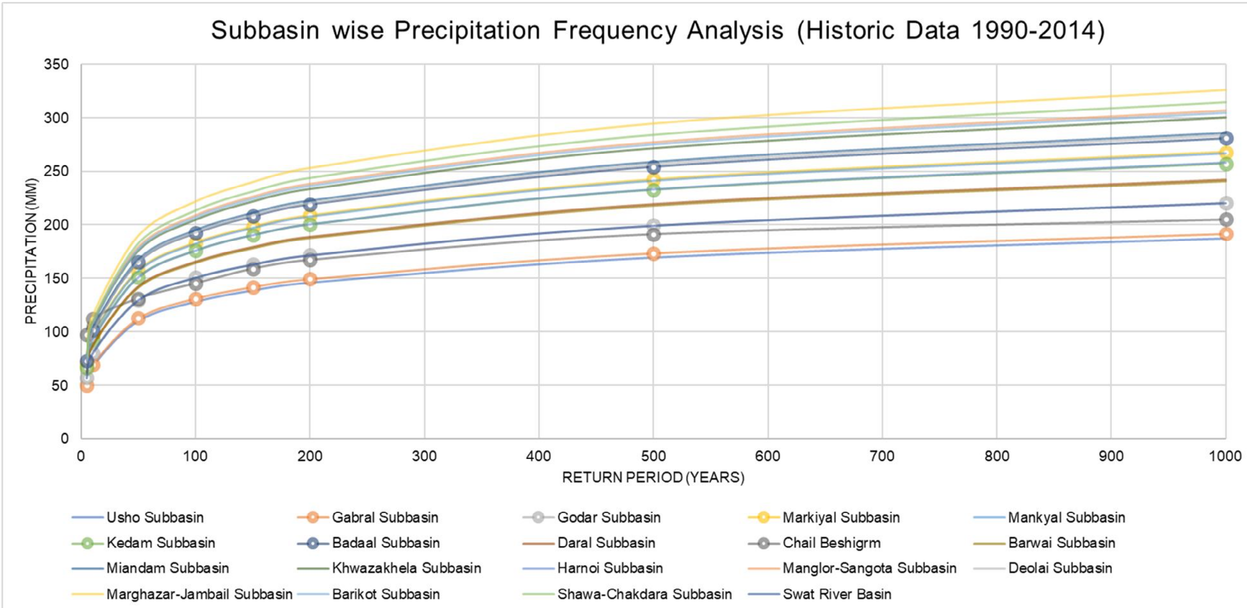

Fig. 3 Subbasin wise Precipitation Frequency Analysis (Historic Data)

Table 2. Subbasin wise Precipitation Frequency Analysis (SSP2 4.5)

S #	Subbasins	Precipitation (mm) SSP2 4.5 (2025-2099)							
		Return Periods (yr)							
	Return Year Period (yr)	5	10	50	100	150	200	500	1000
1	Usho Subbasin	55	77	125	145	157	165	192	212
2	Gabral Subbasin	56	78	128	148	160	169	196	217
3	Godar Subbasin	65	90	147	171	185	194	226	250
4	Markiyal Subbasin	79	110	179	208	224	237	275	303
5	Mankyal Subbasin	78	110	178	207	223	235	273	302
6	Kedam Subbasin	75	105	171	199	215	227	264	291
7	Badaal Subbasin	83	115	187	218	236	248	288	318
8	Daral Subbasin	71	99	161	188	203	214	248	275
9	Chail Beshigram	80	112	182	212	230	242	281	311
10	Barwai Subbasin	70	98	160	186	202	213	247	273
11	Miandam Subbasin	83	116	190	221	240	252	293	324
12	Khwazakhela Subbasin	87	122	199	232	251	265	308	341
13	Harnoi Subbasin	74	104	171	199	216	227	265	293
14	Manglor-Sangota Subbasin	88	124	204	237	257	271	315	348
15	Deolai Subbasin	81	114	187	219	237	249	290	321
16	Marghazar-Jambail Subbasin	93	131	215	251	272	287	334	369
17	Barikot Subbasin	86	122	201	234	254	268	312	345
18	Shawa-Chakdara Subbasin	88	125	207	242	262	277	322	357
19	Swat River Basin at Chakdara	64	90	146	170	184	194	226	249

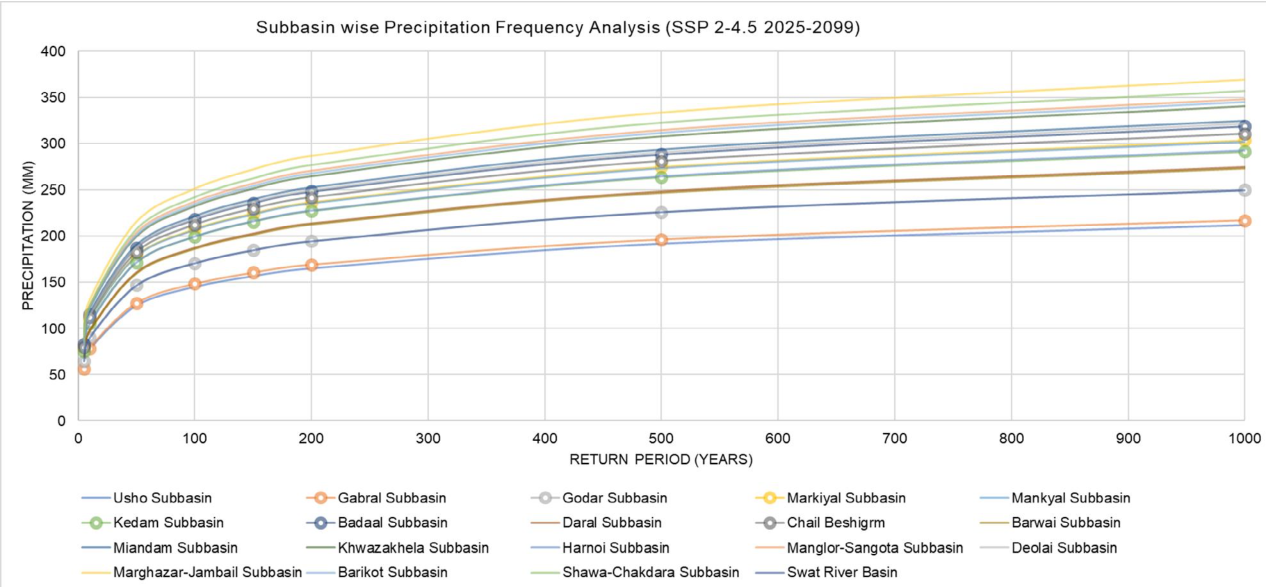

Fig. 4 Subbasin wise Precipitation Frequency Analysis (SSP2 4.5)

V. CONCLUSIONS

The significance of precipitation frequency analysis in the context of flood risk assessment and the design of hydraulic structures in the Swat River Basin is clearly highlighted in this research. The results showed that the spatial variability in extreme precipitation values over the sub-basins was quite high. The factors that contributed to this were the topography and the elevation of the area. The sub-basins that were identified in this study as high-risk areas were Manglor-Sangota, Marghazar-Jambail, and Barikot due to the significantly higher precipitation values in these areas.

The comparison of historical data with the SSP2-4.5 climate scenario showed that the magnitudes of extreme precipitation values are increasing over the years. This indicates that the impact of climate change on the hydrological cycle is becoming more prominent.

The significance of this research is that it provides valuable information for the planning and designing of hydraulic structures. The flood hazard in the sub-basins can be assessed individually. The appropriate return period for the design of the hydraulic structure can be determined. The significance of this research is that it provides valuable information for the planning and designing of hydraulic structures. The necessity of adopting climate-informed and localized approaches in the context of water resources engineering is highlighted in this research.

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