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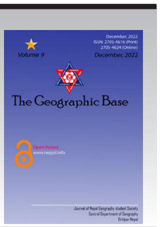

Comparative Study of Flood and Long-term Mean Monthly Flow Estimation Approaches: Case Studies of Six Basins in Nepal

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Abstract

Most of Nepal's river basins have poor hydro-meteorological databases, with several river basins being ungauged. Thus, hydrological parameters need to be estimated using different types of computation methods. The primary goal of this study is to identify the most accurate method for calculating peak flood and long-term mean monthly flow among the most commonly used methods in Nepal. We compared the peak flood calculated using various flood computation formulas, such as Hydest, Modified Hydest, MHSP (Medium Hydropower Study Project) 1997, Modified Dickens, PCJ (Prem Chandra Jha) 1996, Rational, and Specific Discharge, to the flood calculated using gauged discharge data frequency analysis. We find that it is wise to use the Modified Hydest method in the khokana basin for all Return Periods (RPs) and in the Belkot basin (for RP $\leq$ 100 years), the Specific Discharge method in the Jamu basin, the MHSP 1997 method in the Belkot basin (for RP $\leq$ 100 years) and the Bagasoti Gaun basin (for RP $\leq$ 20 years). The PCJ 1996 method having the *lowest cumulative value of Root Mean Square Error (RMSE) for the six studied catchments is suitable for Rabhuwa Bazar (for RP > 50 years) and Bagasoti Gaun (for RP >20 years). Similarly, the Modified Dickens method is suitable in the Bagasoti Gaun basin for RP ≤ 50 years. This paper also shows the performance of the Hydest and MHSP 1997 mean flow estimation methods and suggests different coefficients or constants to be used with the MHSP 1997, Modified MIP (Medium Irrigation Project), and Hydest methods to obtain more reliable long-term mean monthly flows. Overall, our study will help the designer choose a reliable method for design flow estimation. This study also shows that the flow obtained from even the most suitable methods needs to be adjusted. As a result, intensive research is required to adjust previous methods and develop the new one.*

Introduction

Flood-related studies are gaining popularity regarding the construction of storage structures, watershed management, flood protection, water resource planning, development, and management (Jarosińska & Pierzga, 2017; Keskin et al., 2020; Subedi et al., 2023). However, insufficient hydrological data for flood study is a major problem in a developing country like Nepal (Acharya & Joshi, 2020). So, Nepal profoundly depends on empirically derived equations to calculate peak and mean monthly flows for designing hydraulic structures and carrying out river training works. Estimating peak flood at ungauged sites and sites with limited time series data is challenging as it demands the identification and development of pertinent flood computational techniques (Moges & Taye, 2019). There are various methods of estimating peak flood and long-term mean monthly flow using parameters like rainfall, steepness of the basin, surface characteristics of the catchment area, etc., in the ungauged river basin. However, these methods are highly susceptible to heavy errors due to their distinct postulates (Rijal, 2014). The reliability of the limited data available is also questionable. In addition, meager investigations comparing discharge computation approaches have been made till date (Basnet et al., 2018). This has engendered a great challenge in the accurate estimation of peak flood discharge and mean monthly flow. Inability of accurate peak flood and mean discharge estimation is accountable for damages to water resources projects like hydropower, irrigation, water supply, etc., and road infrastructures like bridges, culverts, side drains, etc., which will ultimately lead to losses in life and economy (Smithers, 2012). So, selection of the best approach for peak flood computation is an indispensable need (Keskin et al., 2020).

In the case of gauging stations, many frequency distribution models have been developed for peak flood estimation, but none of them are universally undertaken as relevant distribution models because their fitness for any location is contingent upon the nature of available data (Hassan et al., 2019). Among seven methods (Rational, PCJ 1996, Soil Conservation Services (SCS), Modified Dicken's, Sharma and Adhikari, Tahal et al. (2002), and Water and Energy Commission Secretariat/Department of Hydrology and Meteorology (WECS/DHM)) of peak flood estimation, the PCJ 1996 method was found to have a higher closeness with results obtained from the frequency analysis of gauged data in the Rapti river basin, Nepal (Rijal, 2014). Similarly, the catchment area ratio (CAR) method was found to have greater accuracy as compared to MIP, the National Resources Conservation Service-Curve Number (NRCS-CN) and the Rational method in calculating the design discharge of a hydropower project at Padhukhola, Kaski, Nepal (Basnet et al., 2018). So, it can't be generalized that the same method will always provide the closest value to that obtained from the frequency analysis of the gauged data. So, the purpose of this research paper is to identify the best approach for peak flood estimation by comparing the closeness of the results obtained from the seven most commonly used flood computational techniques in Nepal to those obtained from the best fit probability distribution function for gauged hydrological data, and also to compare and adjust the empirical methods for long-term Mean Monthly Flow (MMF) estimation by comparing their results with the measured values. The outcome of this paper will aware the researchers and the designers that the Gumbel's Distribution, Log-Normal Distribution, and the Log-Pearson Type III Distribution that are commonly used for frequency analysis may not always be the best fit probability distribution for the hydrological time series data of different location.

Methods and Materials

Study area

Our study area comprises of small sized catchment to large sized catchment from eastern Nepal to western Nepal as shown in Figure 1. The rationales behind the selection of these six particular catchments are the availability of the hydrological data at the outlet of the basin, as it can be used for assessing the accuracy of studied flow computational methods and to provide a general overview about the suitability of various flood and long-term mean monthly flow calculation approaches in overall Nepal. The six basins were delineated from the NASA shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of 30m resolution using ArcGIS software. Index number of outlet discharge stations along with its catchment name, area, elevation range, latitude range, longitude range and index number of considered rain gauge stations for six catchments are shown in Table 1. Dudhkoshi of Rabhuwa Bazar, Bagmati of Khokana, Tadikhola of Belkot, Lothar River of Lothar, Bheri River of Jamu and Rapti River of Bagasoti Gaun are the major river systems of various catchments of our study area. The coordinates of outlets are (27.27056°N, 86.66722°E), (27.62889°N, 85.29472°E), (27.85972°N, 85.13833°E), (27.58722°N, 84.73528°E), (28.75556°N, 81.35°E) and (27.85333°N, 82.79278°E) for Rabhuwa Bazar, Khokana, Belkot, Lothar, Jamu and Bagasoti Gaun respectively. Each outlet point is the location of the discharge station. All catchments are named after the name of their outlet hydrological station. Average monsoon precipitation of Rabhuwa Bazar, Khokana, Belkot, Lothar, Jamu and Bagasoti Gaun are 1800mm, 1000mm, 2000mm, 2000mm, 1385mm and 1000mm approximated from the rainfall data.

The temperature range for the six studied catchment ranges from the annual maximum temperature of 46°C at Bagasoti Gaun (Pandey et al., 2021) to annual minimum temperature of -2.45°C at Northern region of Rabhuwa Bazar Catchment (Bocchiola et al., 2020). Similarly, the highest annual rainfall of 2431 mm was observed at Belkot Catchment (Bhusal & Marahatta, 2008) and the lowest annual rainfall of 446 mm at Rabhuwa Bazar Catchment (Bocchiola et al., 2020).

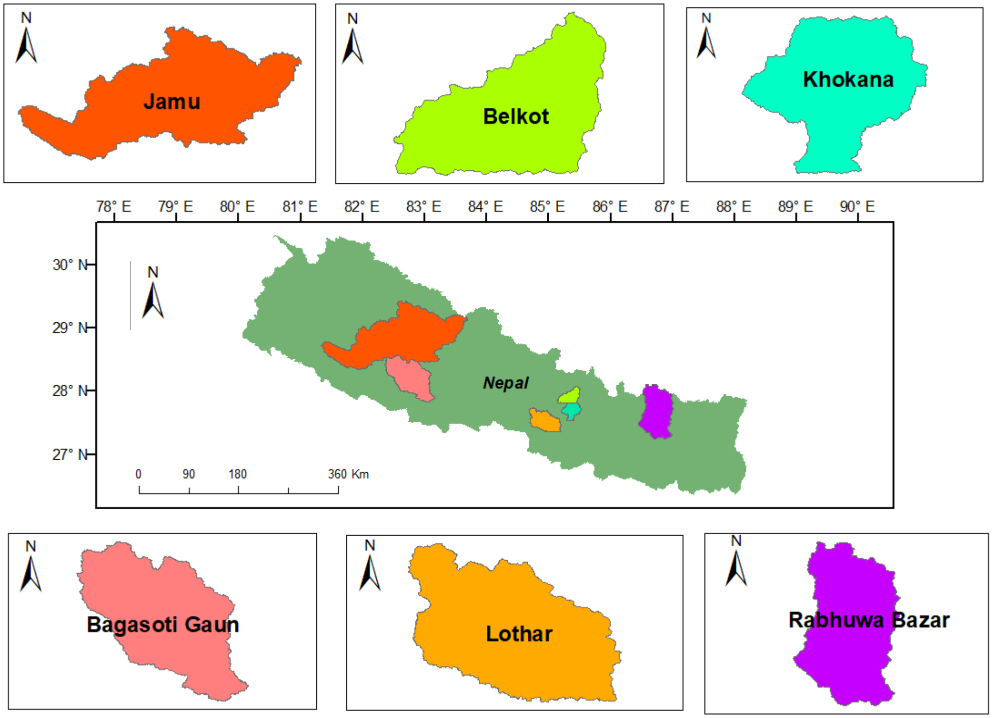

Figure 1. Location of Study Area

Table 1. Characteristics of six different catchments considered for our study

Index no. of outlet discharge station	Catchment name	Area (km^2)	Elevation range (ma.s.l.)	Latitude range	Longitude range	Index no. of considered rain gauge stations
670	Rabhuwa Bazar	3711	450-8821	27.241606°N-28.113441°N	86.433333°E-86.981684°E	1202, 1203, 1204, 1219
550.05	Khokana	609	1260-2729	27.536925°N-27.817517°N	85.188931°E-85.524775°E	1015, 1022, 1029, 1030, 1035, 1038, 1039, 1043, 1052, 1059, 1060, 1071, 1073, 1074, 1075, 1076, 1077, 1079, 1080, 1081, 1082
448	Belkot	652	492-5099	27.806564°N-28.083282°N	85.130227°E-85.494632°E	1004, 1007, 1017, 1038, 1055, 1058, 1071, 1074, 1081
470	Lothar	170	336-1570	27.736283°N-27.570262°N	84.822738°E-84.676868°E	903, 1005, 905, 902
270	Jamu	13793	260-6351	28.337720°N-29.426502°N	81.326359°E-83.680844°E	511,406,410,403,301, 502,413,501,312,402, 404, 513, 310, 401, 418,304,615,304,616,308, 514, 629, 625, 624, 628, 405, 412
350	Bagasoti Gaun	3589	333-3653	27.828001°N-28.571509°N	82.349307°E-83.160278°E	504,512,509,721,505 722,725,715,615,501, 514,502

Materials

The instantaneous discharge, the long-term mean monthly flow and the extreme rainfall data were bought from DHM. Stations with missing data of less than 5% for a range of dates for which data is available are considered for our study. Missing instantaneous discharge data was filled by using the long-term average method. Extreme rainfall data for a given basin was calculated by providing thiessen weightage to the different stations lying within and around it. In the scenario in which the extreme rainfall data of a given station was missing, we have excluded that station for that date only while providing the thiessen weightage. The details of hydro-meteorological data used in our study are provided in Table 2.

The DEM of 30 m resolution was used for the catchment delineation and it was obtained from https://www.usgs.gov/. Land use/land cover (LULC) data of 2010, provided by the International Center for Integrated Mountain Development (ICIMOD), was used for the calculation of equivalent runoff coefficient of our studied catchments.

Table 2. Hydro-meteorological data used for study

Stations name (Index number)	Parameters used	Date range
Jamu (270)	Instantaneous discharge	1963-2015
Bagasoti Gaun (350)	Instantaneous discharge	1976-2015
Belkot (448), Lothar (470)	Instantaneous discharge	1969-2015
Khokana (550.05)	Instantaneous discharge	1992-2015
Rabhuwa Bazar (670)	Instantaneous discharge	1964-2014
Mugu (301), Guthi Chaur (304), Magma (308), Dipal Gaun (310), Dailekh (402), Jamu (Tikuwakuna) (403), Jajarkot (404), Chispani (Karnali) (405), Surkhet (Birendranagar) (406), Bale Budha (410), Naubasta (412), Naubasta (412), Shyano shree (Chepang) (413), Maina Gaun (418), Salyan Bazar (511), Chaur Jhari (513), Gurja Khani (616), Samar Gaun (624), Sanda (625), Muna (628), Baghara (629)	Extreme rainfall	1975-2015
Rukumkot (501), Libang Gaun (504), Bijuwa Tar (505), Ghorahi (Masina) (509), Luwamjula Bazar (512), Musikot (Rukumkot) (514), Bobang (615), Pattharkot (721), Musikot (722), Tamghas (725), Khanchikot (715)	Extreme rainfall	1986-2014
Chaurikhark (1202), Pakarnas (1203), Aisealukhark (1204), Salleri (1219)	Extreme rainfall	1983-2013
Tikathali (1080), Jetphurphedi (1081), Nangkhel (1082)	Extreme rainfall	2000 -2015
Rampur (902), Jhawani (903), Daman (905), Godavari (1022), Khumaltar (1029), Kathmandu Airport (1030), Sankhu (1035), Panipokhari (Kathmandu) (1039), Nagarkot (1043), Bhaktapur (1052), Changunarayan (1059), Chapagaun (1060), Khokana (1073), Dhading (1005), Thankot (1015), Nuwakot (1004), Kakani (1007), Dubachaur (1017), Dhunibesi (1038), Dhunche (1055), Tarke Ghyang (1058), Budhanilkantha (1071)	Extreme rainfall	1992-2015
Naikap (1076), Sundarijal (1077), Sundarijal (1074), Lele (1075), Nagarjun (1079)	Extreme rainfall	1998-2015

Methodology

In order to approximate the magnitude of a flood peak and mean monthly flow (MMF), different methods were applied based upon the desired objective and availability of data. Method of frequency analysis (Malik & Pal, 2021) was used for the values of annual maximum flood of a large number of successive years to estimate flood discharge of various return period. Similarly, most commonly practiced peak flood and MMF computational formulas in Nepal were also used for assessing their accuracy. Flood discharges of various return periods obtained from the best fit frequency distribution model and the long-term MMF obtained from DHM were juxtaposed with that elicited from different flood computational technique to point out appropriate formulas for our study area. Methodological framework for this study is shown in Figure 2.

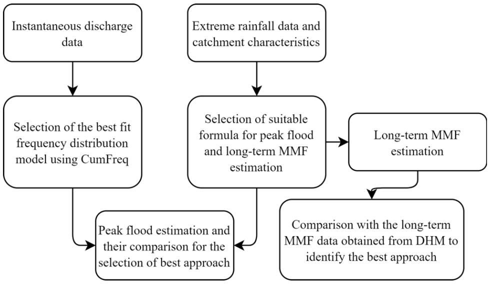

Figure 2. Methodological framework

(a) Best fit probability distribution

The CumFreq model program, developed by the Institute for Land Reclamation and Improvement (ILRI) in Netherlands was used to perform probability distribution fitting of hydrological extreme data series (Ionuş et al., n.d.). The "Best of All distributions" option in CumFreq software was used to obtain best fitted distribution models for extreme discharge of studied catchments. Based on best fitted distribution models, discharges of various return periods were calculated for respective catchments.

(b) Peak flood estimation approaches

Rational method

A Rational formula that considers the area, shape, slope, permeability, and initial wetness of the basin as well as the intensity, distribution, and duration of rainfall can be used to estimate flood flows (WECS, 2019). As per WECS, for small catchments up to 50 km^2, rational formula could be used. However, in practice, this method has also been widely applied over much larger areas in Nepal (Rijal, 2014). Expression for rational formula is given in equation 1.

$$Q = \frac{CIA}{3.6} \quad \ldots\ldots \ (1)$$

Where, Q = maximum flood discharge in m^3/s for return period T, C = runoff coefficient, I = mean intensity of rainfall in mm/hour for return period T, and A = area of basin in km^2. Coefficient of runoff was taken as 0.3 for forest, shrub land and grassland, 0.5 for agriculture, 0.25 for barren area, 0.865 for built-up area, 0.01 for water body and 0.9 for snow/glacier by analyzing many literatures (Mahmoud & Alazba, 2015; Sriwongsitanon & Taesombat, 2011).

For mean intensity of rainfall, frequency analysis has been carried out using yearly maximum 24 hours rainfall data bought from the Department of Hydrology and Meteorology (DHM). Gumbel distribution was used for projecting rainfall data to different return periods.

The value of the variate X with a recurrence interval T can be computed with the aid of equations 2, 3 and 4.

$$X_T = \bar{X} + K\sigma_{N-1} \quad \text{......} \quad (2)$$

$$K = \frac{y_T - \bar{y}_n}{S_n} \quad \text{......} (3)$$

$$y_T = -ln\left(ln\left(\frac{T}{T-1}\right)\right) \quad \text{......} \quad (4)$$

Where, y_T= reduced variate, a function of T, σ_{N-1}= Standard deviation of the sample of size N, K= frequency factor, $\bar{y}_n$ = reduced mean, a function of sample size N, S_n = reduced standard deviation, a function of sample size N. In a Thiessen polygon network, the corresponding areas of application are used to calculate the relative weights for each gauge (Olawoyin, 2017). Intensity of rainfall corresponding to the time of concentration can be estimated from Mononobe's equation given in equation 5 (Faradiba, 2021).

$$I_{tc} = \left(\frac{R}{24}\right) * \left(\frac{24}{t_c}\right)^{\frac{2}{3}} \quad \text{......} (5)$$

Where, R is 24-hour rainfall and t_c is time of concentration in hours. It was estimated using Kirpich formula provided in equation 6 (Perdikaris et al., 2018).

$$t_c = 0.00032L^{0.77}S^{-0.385} \quad \text{......} \quad (6)$$

Where L is the maximum distance that water is able to flow in meters, S is the slope which is equal to H/L, and H is the distance in meters between the remotest point of the basin and the outlet.

Modified dickens method

This method is widely used in Nepal (Rijal, 2014). The irrigation research institute, Roorkee India has performed frequency studies of river discharge on Himalayan Rivers & recommended the modified or revised relationship as shown in equation 7 to compute the flood discharge of various return periods using Dicken's constant obtained using equations 8 and 9.

$$Q_T = C_T A^{\frac{3}{4}} \quad \text{......} (7)$$

Where, Q_T is maximum flood discharge(m^3/s) in T years, A is Catchment area (Km^2) and C_T is modified dickens constant suggested by the Irrigation Research Institute, Roorkee, based on frequency studies of river flow on Himalayan rivers.

$$C_T = 2.342\, log(0.6T)\, log\left(\frac{1185}{p}\right) + 4 \quad \text{......} (8)$$

$$p = 100\left(\frac{a+6}{A+a}\right) \quad \text{......} (9)$$

Where, a = perpetual snow area in Km^2 and T = return period in years. Permanent snow area was considered to be present at all attitudes above 5000m (Rees et al., 2004).

WECS/DHM-1990 or Hydest method

In the Nepalese context, WECS developed an empirical method for analyzing floods of different frequency (Acharya & Joshi, 2020). For this purpose, the whole country is considered a single hydrological region, and the method is suitable for any basin with an area of less or equal to 100 km$^{2.}$ (Basnet & Acharya, 2019). Instantaneous peak flood discharge for return periods of 2 and 100 years can be computed using equations 10 and 11, respectively.

$$Q_2 = 1.8767(A_{3000} + 1)^{0.8783} \quad \ldots\ldots(10)$$

$$Q_{100} = 14.63(A_{3000} + 1)^{0.7342} \quad \ldots\ldots(11)$$

After that, floods of different return periods can be estimated by either using algebraic equations or by simply plotting the 2 year and 100 year floods on a piece of paper with log normal probability, which yields a straight line (Department of Electricity Development, 2006). Peak flood discharge for others return period were computed using equations 12 and 13.

$$Q_T = e^{(ln Q_2 + s\sigma)} \quad \ldots\ldots(12)$$

$$\sigma = \frac{ln\left(\frac{Q_{100}}{Q_2}\right)}{2.326} \quad \ldots\ldots(13)$$

Where, Q_2 and Q_{100} are 2 and 100 years return period floods respectively, A_{3000} is the catchment area under 3000 m elevation and S is Standard normal variate whose value depends on return periods. Values of Standard variates are 1.282, 1.645, 2.054, 2.326, 2.576, 2.787 for 10, 20, 50, 100, 200 and 500 years return period respectively (Basnet et al., 2018).

Hydest 2004 DHM or Modified Hydest method

This is the modified version of Hydest 1990. Instantaneous peak flood discharges for return periods of 2 and 100 years can be computed using equations 14 and 15, respectively.

$$Q_2 = 2.29(A_{3000})^{0.86} \quad \ldots\ldots(14)$$

$$Q_{100} = 20.7(A_{3000})^{0.72} \quad \ldots\ldots(15)$$

Peak flood discharge for other return periods were computed using equations 16 and 17.

$$Q_T = e^{(ln Q_2 + s\sigma)} \quad \ldots\ldots(16)$$

$$\sigma = \frac{ln\left(\frac{Q_{100}}{Q_2}\right)}{2.326} \quad \ldots\ldots(17)$$

where, Q_2 and Q_{100} are 2 and 100 years return period floods respectively, A_{3000} is the catchment area under 3000 m elevation and S is Standard normal variate whose value depends on return period. Values of Standard variates for different return periods are as alike as in Hydest method (Basnet et al., 2018).

MHSP 1997 method

Based on MHSP method, the peak flood Q in *m*^{3}*/s* shall be estimated using equation 18 (Department of Electricity Development, 2006).

$$Q = k\,A^b \quad \ldots\ldots(18)$$

Where, constants k and b depend on RP T as shown in Table 3.

Table 3. K and b constants for MHSP method (Source: https://lib.icimod.org/record/4202)

Return period	Regions					
	Western		Central		Eastern	
	k	b	k	b	k	b
5	2.0409	0.8632	1.6762	0.9660	7.4008	0.7862
20	3.2895	0.8510	3.2303	0.9281	13.0848	0.7535
50	4.2570	0.8444	4.6090	0.9071	17.6058	0.7380
100	5.2225	0.8352	5.9865	0.8888	21.5181	0.7281
1000	9.2290	0.8148	12.6603	0.8429	39.9035	0.6969
1000	14.4580	0.8063	24.6431	0.8019	69.7807	0.6695

PCJ (1996) method

According to the PCJ approach, design peak flood discharge is determined by hourly rainfall intensity. (Jha, 2006). Equations used in PCJ method is provided in equations 19 and 20.

$$Q_p = 16.67\, a_p O_p \phi F k_f + Q_S \quad \dots\dots (19)$$

$$a_p = a_{hr} k_t \quad \dots\dots (20)$$

Where,

Q_p = Maximum rainfall design discharge for required exceedance probability (p) in m^3/sec

a_p= Maximum rainfall design intensity for required exceedance probability (p) in mm/min

a_{hr}= Hourly rainfall intensity for required exceedance probability (p) in mm/min at selected rainfall stations

k_t= Reduction coefficient of hourly rainfall intensity (depends on the size of catchment area)

O_p= Infiltration coefficient of the basin, derived as the function of exceedance probability (p)

ϕ = Areal reduction coefficient of maximum rainfall discharge (depends on the size of catchment)

F = Catchment area of drainage basin in sq. km.

k_f= Coefficient for unequal distribution of rainfall in different size of basin, captured by one rain.

Q_S= Discharge by melting of snow, can be taken as 0 to 10% of Q_p in the absence of data.

Specific discharge method

This method was derived from the flood frequency analysis of data up to 1996 for 51 stations of Nepal. Since the data used does not include basins smaller than 12 km^2, this method could not be used for basins with catchment size below 12 km^2 (WECS, 2019). Specific Discharge for 2-year, 25- year, 50- year and 100 year shall be computed using the relation provided in equations 21, 22, 23 and 24, respectively.

$$q_2 = 4.2(Basin\ Area)^{-0.3} \quad \ldots\ldots(21)$$

$$q_{25} = 30.8(Basin\ Area)^{-0.44} \quad \ldots\ldots(22)$$

$$q_{50} = 43.3(Basin\ Area)^{-0.46} \quad \ldots\ldots(23)$$

$$q_{100} = 61.4(Basin\ Area)^{-0.49} \quad \ldots\ldots(24)$$

Where, specific discharge (q) is expressed in $m^3/s/km^2$ and basin area in km^2. Then, flood peaks have been obtained by multiplying the specific discharge with the corresponding area of catchment.

(c) Mean discharge calculation

Modified MIP method

For the application of MIP method, Nepal has been divided into seven hydrological zones (Basnet & Acharya, 2019). The coefficient for different months is obtained based on the hydrological region in which the catchment lies in. As most of our catchments lie at more than one regions demarcated by MIP method, each catchment is considered as a single hydrological zone and Modified MIP constants are defined for each catchment in a similar manner as done by MIP method. Modified MIP constants were determined using equation 25.

$$Modified\ MIP\ constant\ of\ a\ month = \frac{Long\ term\ monthly\ flow\ of\ that\ month}{Long\ term\ mean\ april\ flow} \quad \ldots\ldots(25)$$

WECS/DHM- 1990 (Hydest) method

It was developed collaboratively by WECS and DHM and is a modification of the WECS approach of 1982 (Rijal, 2014). It considers the country as a whole as one hydrological region (Shrestha et al., 1970). This method is appropriate for any catchment with area ≥100 km^2 (Basnet & Acharya, 2019).

The average monthly flows can be calculated by using equation 26.

$$Q_{mean}^{monthly} = C(Area\ of\ Basin)^{A1}(Area\ below\ 5000m + 1)^{A2}(MMP)^{A3} \quad \ldots\ldots(26)$$

Where, mean monsoon precipitation (MMP) can be obtained from monsoon precipitation isolines (mm) provided by the Department of Hydrology and Meteorology, Nepal. C, A1, A2 and A3 are coefficients whose values are obtained from Table 4.

Table 4. Values of Various coefficients for WECS/DHM (Hydest) Method (Source: https://lib.icimod.org/record/4202)

Month	C	A1	A2	A3
Jan	0.0142	0.0000	0.9777	0.0000
Feb	0.0122	0.0000	0.9766	0.0000
Mar	0.0100	0.0000	0.9948	0.0000
Apr	0.0080	0.0000	1.0435	0.0000
May	0.0084	0.0000	1.0898	0.0000
Jun	0.0069	0.9968	0.0000	0.2610
Jul	0.0212	0.0000	1.0093	0.2523
Aug	0.0255	0.0000	0.9963	0.2620
Sep	0.0168	0.0000	0.9894	0.2878
Oct	0.0097	0.0000	0.9880	0.2508
Nov	0.0018	0.9605	0.0000	0.3910
Dec	0.0015	0.9605	0.0000	0.3607

MHSP 1997 method

In 1997, the MHSP under the Nepal Electricity Authority (NEA) developed a method to estimate long-term flows, flood flows, and flow duration curves at ungauged sites (Pathak, 2012). Data required for obtaining MMF are monsoon wetness index and average precipitation of the area along with the river catchment. In case if the long-term rainfall data are available, monsoon wetness index can be taken as equivalent to average of rainfall data from June to September in various years. Equation 27 was used for calculation of long-term mean monthly flow as per MHSP 1997 method.

$$Q^{monthly}_{mean} = C(Area\ of\ Basin)^{A1}(Mean\ Monsoon\ Precipitation)^{A2} \text{ ……(27)}$$

Table 5 shows the value of various constants derived from regression equations to be used in MHSP 1997 method.

Table 5. Values of various coefficients for MHSP 1997 method (Source: https://lib.icimod.org/record/4202)

Month	C	A1	A2
Jan	0.0312	0.8644	0.0000
Feb	0.0242	0.8752	0.0000
Mar	0.0205	0.8902	0.0000
Apr	0.0178	0.9558	0.0000
May	0.0119	0.9657	0.0000
Jun	0.0114	0.9466	0.2402
Jul	0.0164	0.9216	0.3534
Aug	0.0259	0.9095	0.3242
Sep	0.0221	0.8963	0.3217
Oct	0.0150	0.8772	0.2848
Nov	0.0079	0.8804	0.2707
Dec	0.0054	0.8890	0.2580

Results and Discussion

Extreme discharge

The list of different distributions showing the best fit for discharge data of different catchments along with the test parameters as calculated from CumFreq is shown in Table 6. Table 7 shows the discharge of 10, 20, 50, 100, 200 and 500 year return periods for six different catchments obtained by using seven different flood computational formulas (Hydest, Modified Hydest, MHSP 1997, Modified Dickens, PCJ, Rational and Specific discharge method). The discharges of various return periods for different basins obtained from frequency analysis of data by selecting best distribution model from Cumfreq software is also shown in last column of the Table 7.

Table 6. Selection of best fitted distribution from CumFreq software for extreme flow data of various catchments

Stations	Distribution	(Coefficient of determination) R^2	% Averages of absolute difference in observed and estimated cumulative frequency.
Jamu	Dagum distribution generalized	0.9884	2.5154
Lothar	Generalized Laplace distribution	0.9846	2.585
Rabhuwa Bazar	Generalized extreme value (GEV) distribution	0.9928	1.91
Belkot	Dagum distribution generalized	0.9902	2.07
Khokana	Generalized Laplace distribution	0.9842	2.71
Bagasoti Gaun	Generalized Laplace distribution	0.978	3.19

Here, results obtained from best fitted distribution model is considered as true value and discharge of various return periods obtained from seven different flood computation methods are considered as predicted value and based on this, value of root mean square error (RMSE) is calculated (Tegegne et al., 2020). The cumulative value of RMSE for all six studied catchment is shown in Figure 3. Minimum value of RMSE in our study area is found to be 206.42 cumecs in Belkot as per modified Hydest whereas, maximum value is 3735.54 cumecs at Rabhuwa Bazar for output of Rational method.

Table 7.a. Extreme discharges (Cumecs) and RMSE (Cumecs) calculation.

7.a. Extreme discharge for Rabhuwa Bazar								
Return period	Hydest	Modified Hydest	MHSP 1997	Modified Dickens	PCJ (1996)	Rational	Specific Discharge	GEV Distribution
10	1905.68	2245.00	5630.64	3386.88	1539.00	1432.10	2461.22	3001.85
20	2230.66	2702.00	6403.52	3961.29	2679.00	1613.40	2951.65	3657.76
50	2663.68	3328.00	7585.41	4720.63	4238.00	1848.13	3664.73	4685.13
100	2997.24	3824.00	8546.51	5295.05	5388.00	2023.96	4061.03	5612.95
200	3340.55	4344.00	9258.24	5869.46	6310.00	2199.19	4580.82	6698.09
500	3808.11	5068.00	10779.2	6628.80	7756.00	2430.27	5229.13	8422.97
RMSE	*2790.95*	*1971.72*	*2694.85*	*841.46*	*810.75*	*3735.54*	*1775.95*	

Table 7.b. Extreme discharge of Khokana

Return period	Hydest	Modified Hydest	MHSP 1997	Modified Dickens	PCJ (1996)	Rational	Specific Discharge	Generalized Laplace Distribution
10	978.00	1166.00	1045.90	1179.00	445.05	1430.80	868.04	704.60
20	1166.00	1430.00	1241.09	1445.00	664.51	1649.68	1086.65	929.62
50	1422.00	1798.00	1547.70	1797.00	945.73	1932.99	1381.25	1337.07
100	1623.00	2094.00	1787.69	2064.00	1126.53	2145.29	1615.88	1756.36
200	1833.00	2409.00	1962.00	2330.00	1253.05	2356.81	1812.89	2302.89
500	2122.00	2854.00	2378.35	2682.00	1487.25	2635.93	2101.89	3285.46
RMSE	*536.97*	*405.62*	*446.82*	*440.03*	*914.98*	*574.03*	*534.48*	

Table 7.c. Extreme discharge of Belkot

Return period	Hydest	Modified Hydest	MHSP 1997	Modified Dickens	PCJ (1996)	Rational	Specific Discharge	Dagum Distribution Generalized
10	955.73	1141.00	1113.91	1247.63	499.19	1433.43	902.36	925.17
20	1140.66	1399.00	1322.04	1530.46	739.58	1633.43	1127.91	1143.98
50	1392.23	1760.00	1646.29	1904.62	1045.25	1892.31	1432.98	1498.58
100	1589.54	2051.00	1899.20	2187.57	1249.19	2086.31	1672.97	1831.70
200	1795.47	2361.00	2077.13	2470.37	1380.39	2279.60	1877.17	2235.85
500	2080.13	2798.00	2513.25	2844.56	1635.40	2534.60	2175.33	2907.28
RMSE	*397.70*	*206.42*	*213.76*	*317.22*	*734.77*	*378.27*	*340.26*	

Table 7.d. Extreme discharge of Lothar

Return period	Hydest	Modified Hydest	MHSP 1997	Modified Dickens	PCJ (1996)	Rational	Specific Discharge	Generalized Laplace Distribution
10	354.00	430.00	314.22	406.00	342.65	1199.63	420.04	611.97
20	435.00	542.00	370.39	490.00	518.27	1473.96	540.18	809.92
50	548.00	704.00	487.17	601.00	750.43	1829.05	694.11	1169.61
100	639.00	837.00	575.99	685.00	926.05	2095.13	843.66	1541.01
200	736.00	981.00	639.68	769.00	1101.67	2360.25	939.29	2026.52
500	872.00	1189.00	795.05	880.00	1333.84	2710.02	1098.11	2902.35
RMSE	*1095.06*	*898.70*	*1157.79*	*1070.21*	*819.25*	*528.61*	*936.25*	

Table 7.e. Extreme discharge of Jamu

Return period	Hydest	Modified Hydest	MHSP 1997	Modified Dickens	PCJ (1996)	Rational method	Specific Discharge	Dagum Distribution Generalized
10	6538.00	7516.00	9443.33	9614.00	2925.00	4262.54	4937.91	4219.30
20	7392.00	8746.00	10964.40	11364.00	4798.77	4581.46	5800.60	5192.84

50	8488.00	10373.00	13324.07	13677.00	7270.00	4994.28	7445.73	6784.30
100	9306.00	11620.00	14973.62	15427.00	9044.00	5303.63	7932.27	8285.15
200	10127.00	12898.00	16211.78	17176.00	10374.71	5611.85	9903.13	10108.80
500	11216.00	14630.00	19125.78	19489.00	12593.59	6018.49	12252.20	13141.07
RMSE	*1725.48*	*3095.42*	*6071.36*	*6531.24*	*708.60*	*3728.78*	*616.46*	

Table 7.f. Extreme discharge of Bagasoti Gaun

Return period	Hydest	Modified Hydest	MHSP 1997	Modified Dickens	PCJ (1996)	Rational	Specific Discharge	Generalized Laplace Distribution
10	3968.00	4607.00	2983.78	5108.80	1625.00	4027.19	2413.76	2858.60
20	4549.00	5434.00	3486.78	6367.56	2687.10	4667.45	2897.19	3483.04
50	5308.00	6546.00	4274.99	8031.67	4155.00	5497.14	3599.00	4515.85
100	5881.00	7408.00	4864.12	9290.48	5274.00	6122.24	3992.20	5489.98
200	6462.00	8300.00	5286.07	10549.05	6139.83	6743.56	4503.11	6667.91
500	7241.00	9523.00	6296.51	12213.36	7513.81	7561.88	5142.17	8609.15
RMSE	*918.48*	*1739.84*	*1134.55*	*3372.49*	*796.95*	*933.95*	*1840.81*	

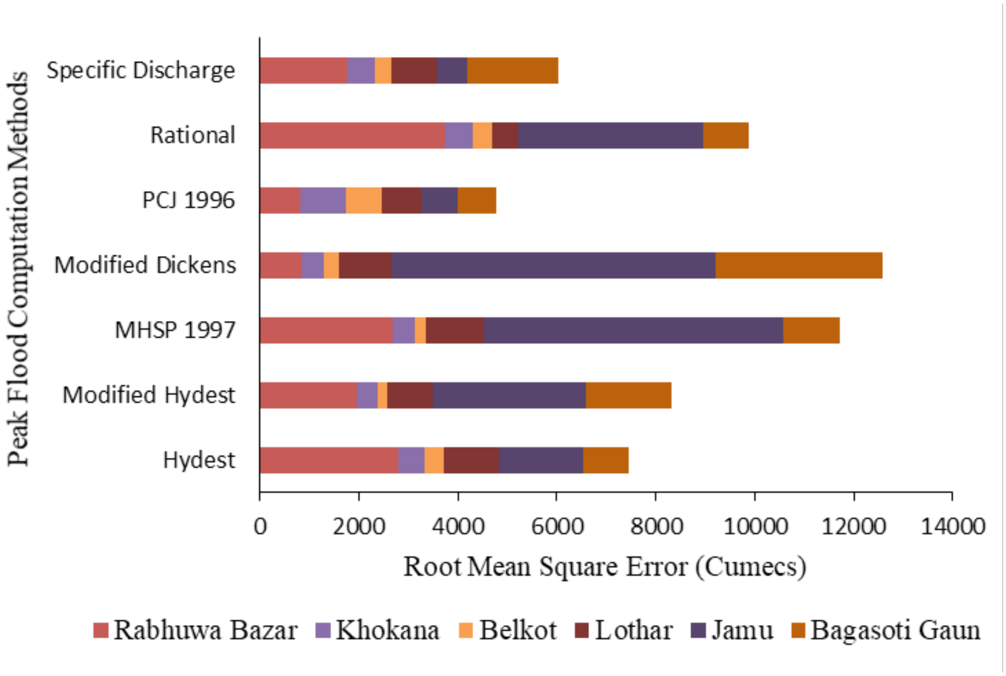

Figure 3. The root mean square (RMSE) of each studied peak flood computation methods in each gauging station

PCJ (1996) method was found to have less variation with the best fitted distribution model in calculation of discharges of various return periods in Rabhuwa Bazar and Bagasoti Gaun, as indicated by RMSE of Table 7 and Figure 4. In Rabhuwa Bazar basin, PCJ method has underestimated the discharge values of various return periods, though having less variation with the discharges of various return periods obtained from the best fitted distribution model. So, Modified Dickens method having comparable RMSE to that of PCJ method in Rabhuwa Bazar could be used for calculation of discharges up to 50 years return period and for calculation of discharges of higher return periods (>50), the PCJ method could be used by increasing its value from 5-10%. Increment should be done by a smaller percentage in calculating discharge of return period slightly greater than 50 and this percentage will increase on moving to higher return periods.

Despite having less RMSE, PCJ method has under predicted discharge values of all return periods in Bagasoti Gaun. So, use of PCJ method in this catchment can only be permitted by certain percentage increments on its estimated value. It would be better to use MHSP 1997 method up to 20-year return period and for other return periods, the PCJ method should be used with percentage increment. 5-10% increment should be done up to 200-year return period. Percentage increment for return periods slightly greater than 200 should be around 10% and this percentage increment should be increased on moving to higher return periods.

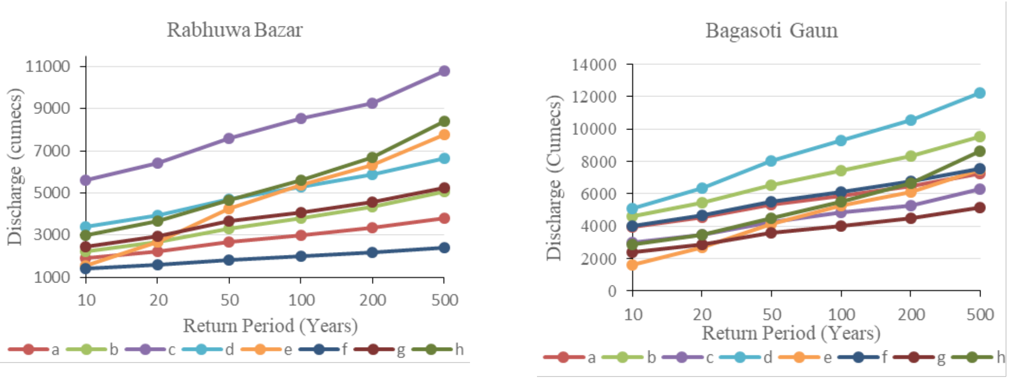

Figure 4. Plot of discharges of various return periods obtained from all considered formulas in Rabhuwa Bazar and Bagasoti Gaun basin (Note: a = Hydest, b = Modified Hydest, c = MHSP 1997, d = Modified Dicken's, e = PCJ 1996, f = Rational, g = Specific Discharge, h = Best Fit Probability Distribution Function for respective basin)

In Khokana and Belkot basins, discharges of various return periods from Hydest 2004 DHM method show less variation with that obtained from best fitted distribution models as indicated by RMSE value in Table 7 and Figure 5. In Khokana basin, up to 200 years return period, Hydest 2004 DHM yields slightly higher value as compared to generalized Laplace distribution (best fitted distribution of Khokana basin) which when adopted for design of hydraulic structures would act as a safety factor. Rapidly rising slope of Generalized Laplace distribution graph in Khokana for return periods greater than 200 demands a certain percent increment in discharge values obtained from Hydest 2004 DHM for return periods greater than 200. Increment should be done by a smaller percentage in calculating discharge of return periods slightly greater than 200 and this percentage increases on moving to higher return periods. Table 7 shows that the increment in discharge obtained from Hydest 2004 DHM for the 500 return period is approximately 15%.

In context of Belkot basin, MHSP 1997 has predicted the discharge values close to that best fitted distribution model up to 100 years return period. For return periods greater than 100 and up to around 350 (350 return period is obtained from visual inspection of graph (D) of Figure 5), Hydest 2004 DHM could be used without altering its output a little. However, for return periods greater than 350, little increment must be made in value obtained from Hydest 2004 DHM. The increment should be 3% in 500 years return period as calculated from data provided in table. Due to higher rising slope of Dagum distribution generalized graph, increment percent should increase on moving to higher return periods. Modified Dickens method though having slightly higher but comparable RMSE over-predict the discharge values up to return periods slightly less than 500. So, modified dickens method is disregarded for Belkot basin.

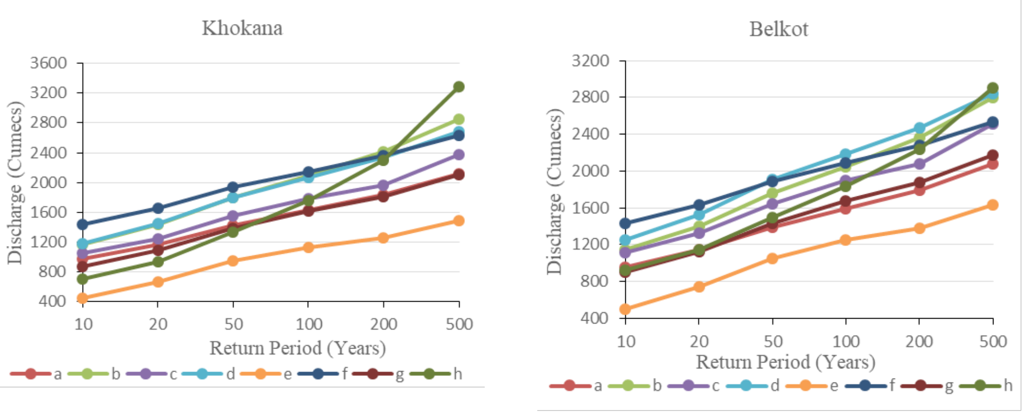

Figure 5. Plot of discharges of various return periods obtained from all considered formulas in Khokana and Belkot basin (Note: a, b, c, d, e, f, g, and h have meaning as in Figure 4)

Results of PCJ and Specific discharge method were found to have less variation with the best fitted distribution model in calculation of discharges of various return periods in Lothar and Jamu basin, respectively, as indicated by RMSE of Table 7 and Figure 6. However, using any studied method for flood estimation of various return period in Jamu is unreasonable without modification. So, an exponential trend line $(Q = 447.31e^{0.3089T})$ was fitted between return period (T) in years and discharge (Q) in cumecs for floods of various return periods obtained from best fitted distribution model. 1-2% increment in discharge value obtained from equation of exponential trend line can act as a safety factor during design.

In case of Jamu basin, Specific discharge method could be adopted up to 50 years return period without modification but when applied for the return periods greater than 50, increment in values predicted as per Specific discharge method must be done by around 10%.

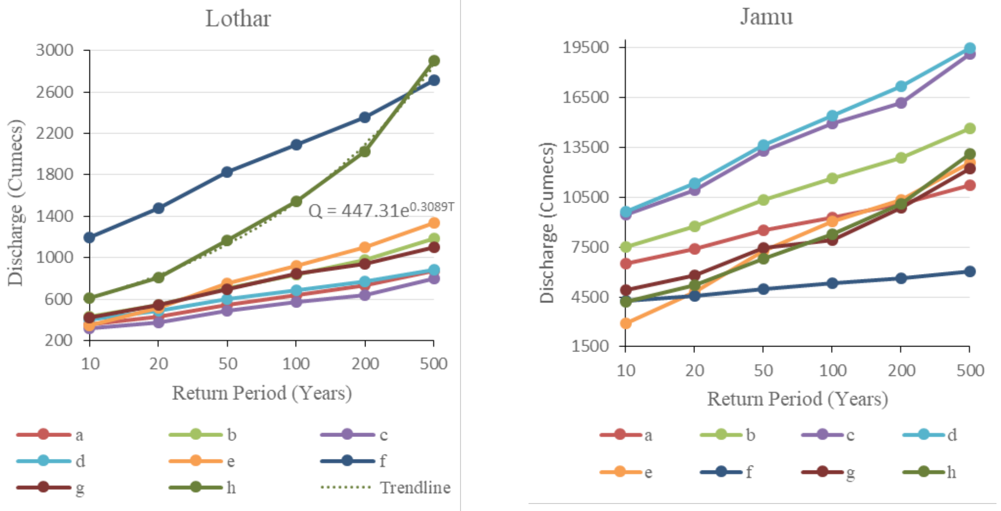

Figure 6. Plot of discharges of various return periods obtained from all considered formulas in Lothar (A) and Jamu (B) basin (Note: a, b, c, d, e, f, g, and h have meaning as in Figure 4)

All the above explanation concerning suitable peak flood computational formulas for calculating peak flood flow is presented in short in Table 8. As the empirical formula for peak flood computation are based on the historical data of the specific location, it might be unable to accommodate the future change in land use pattern and climate due to which different formulas are suitable for different basin in different return period. The Figure 3 shows that the PCJ 1996 method has the least cumulative RMSE and the Modified Dicken's method has the highest cumulative RMSE for the six studied basin. This result suggest that the use of PCJ method is subjected to less risk for the flood computation in the area in which gauged data is not available.

Table 8. Suitable formulas for different basins of Nepal

Catchment name	Suitable peak flood computation method
Rabhuwa Bazar	• Modified Dickens method (upto 50 years return period) • PCJ method with an increment as explained above (for return period higher than 50)
Khokana	• Hydest 2004 DHM method (upto 200 years return period) • Hydest 2004 DHM method with an increment as explained above (for return period greater than 200)
Belkot	• MHSP 1997 method (upto 100 years return period) • Hydest 2004 DHM method (from 100-350 years return period) • Hydest 2004 DHM method with an increment as explained above (for return period greater than 350)
Lothar	• Use of equation $(Q = 447.31e^{0.3089T})$ for peak flood estimation
Jamu	• Specific Discharge method (upto 50 years return period) • Specific Discharge method with an increment as explained above (for return period higher than 50)
Bagasoti Gaun	• MHSP 1997 method (upto 20 years return period) • PCJ method with an increment(for return period higher than 20)

Mean Discharge

Long-term MMF of twelve months as per MHSP 1997 and Hydest for all six studied catchments is shown in Table 9 along with their respective measured long-term MMFs.

Table 9. Measured and calculated value of long-term mean monthly flow in cumecs.

	1. Rabhuwa Bazar			**2.** Khokana			**3.** Belkot		
Month	MHSP 1997	Hydest	Measured	MHSP 1997	Hydest	Measured	MHSP 1997	Hydest	Measured
Jan	37.95	31.24	44.70	7.96	7.53	4.21	7.96	7.53	9.15
Feb	32.16	26.53	36.80	6.61	6.40	3.79	6.61	6.40	7.17
Mar	30.90	25.08	35.60	6.19	5.90	3.00	6.19	5.90	5.00
Apr	46.02	29.38	42.60	8.18	6.43	3.23	8.18	6.43	5.18
May	54.03	44.73	73.40	5.83	9.16	5.58	5.83	9.16	9.43
Jun	156.55	177.54	248.00	25.80	25.14	14.00	25.80	25.14	33.40
Jul	420.75	396.00	573.00	69.47	78.57	43.10	69.47	78.57	96.00
Aug	486.28	461.41	605.00	82.99	92.77	53.00	82.99	92.77	126.00
Sep	364.60	349.00	438.00	63.78	69.81	33.90	63.78	69.81	90.90
Oct	162.34	151.67	192.00	29.82	31.07	13.40	29.82	31.07	41.90
Nov	79.19	88.49	90.20	14.54	12.40	7.18	14.54	12.40	21.00
Dec	52.63	56.21	58.20	9.56	8.48	5.24	9.56	8.48	12.40

	4. Lothar			**5.** Jamu			**6.** Bagasoti Gaun		
Month	MHSP 1997	Hydest	Measured	MHSP 1997	Hydest	Measured	MHSP 1997	Hydest	Measured
Jan	2.65	2.16	1.87	118.05	76.99	103.00	36.87	42.56	27.00
Feb	2.17	1.84	1.56	101.46	65.32	90.60	31.23	36.13	22.30
Mar	1.99	1.66	1.41	99.43	62.81	86.20	29.99	34.36	18.10
Apr	2.42	1.70	1.44	161.38	76.94	104.00	44.57	40.87	15.20
May	2.76	2.28	2.03	191.97	122.27	155.00	32.34	63.15	17.90
Jun	9.12	8.46	4.96	542.40	613.60	324.00	138.28	147.29	71.80
Jul	27.42	25.82	22.10	1410.75	940.69	901.00	356.11	469.92	248.00
Aug	32.60	31.20	30.80	1604.76	1080.26	1260.00	416.39	542.19	380.00
Sep	25.44	24.11	22.50	1182.55	806.42	887.00	312.64	403.05	298.00
Oct	11.88	10.48	9.63	513.49	353.42	373.00	141.28	178.93	108.00
Nov	5.71	4.78	4.54	251.54	281.82	187.00	69.28	68.09	50.20
Dec	3.68	3.09	2.84	169.06	178.83	129.00	46.26	46.60	33.20

While comparing the measured long-term MMFs of various catchments with that obtained from MHSP 1997 and Hydest, neither of the methods has yielded accurate results except for a few months. MIP constants for long-term MMF calculation were not used in our study. However, we have calculated the constant for every month by following the similar procedure as done by MIP method and named it as Modified MIP constants. MHSP 1997 coefficient (A), Hydest coefficient (B) and modified MIP constant (C) for every month are provided for all catchments in Table 10. To get an accurate long-term MMF of respective basins, values obtained from MHSP 1997 and Hydest should be multiplied by their respective coefficients provided in Table 10. However, Modified MIP constants of a basin should be multiplied by their respective long-term mean April flow to generate its long-term MMFs data.

Table 10. Values of coefficient and constant for accurate prediction of long-term MMF

Basin Name	Coefficient or Constant	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rabhuwa Bazar	A	1.178	1.144	1.152	0.926	1.358	1.584	1.362	1.244	1.201	1.183	1.139	1.106
	B	1.431	1.387	1.419	1.45	1.641	1.397	1.447	1.311	1.255	1.266	1.019	1.035
	C	1.049	0.864	0.836	1	1.723	5.822	13.451	14.202	10.282	4.507	2.117	1.366
Khokana	A	0.529	0.573	0.485	0.395	0.957	0.543	0.62	0.639	0.531	0.449	0.494	0.548
	B	0.559	0.592	0.509	0.502	0.609	0.557	0.549	0.571	0.486	0.431	0.579	0.618
	C	1.303	1.173	0.929	1	1.728	4.334	13.344	16.409	10.495	4.149	2.223	1.622
Belkot	A	1.15	1.084	0.808	0.633	1.617	1.294	1.382	1.518	1.425	1.405	1.444	1.297
	B	1.216	1.12	0.848	0.805	1.03	1.328	1.222	1.358	1.302	1.349	1.694	1.462
	C	1.766	1.384	0.965	1	1.82	6.448	18.533	24.324	17.548	8.089	4.054	2.394
Lothar	A	0.706	0.719	0.709	0.595	0.736	0.544	0.806	0.945	0.884	0.811	0.795	0.772
	B	0.866	0.848	0.849	0.847	0.89	0.586	0.856	0.987	0.933	0.919	0.95	0.919
	C	1.299	1.083	0.979	1	1.41	3.444	15.347	21.389	15.625	6.688	3.153	1.972
Jamu	A	0.873	0.893	0.867	0.644	0.807	0.597	0.639	0.785	0.75	0.726	0.743	0.763
	B	1.338	1.387	1.372	1.352	1.268	0.528	0.958	1.166	1.1	1.055	0.664	0.721
	C	0.99	0.871	0.829	1	1.49	3.115	8.663	12.115	8.529	3.587	1.798	1.24
Bagasoti Gaun	A	0.732	0.714	0.603	0.341	0.554	0.519	0.696	0.913	0.953	0.764	0.725	0.718
	B	0.634	0.617	0.527	0.372	0.283	0.487	0.528	0.701	0.739	0.604	0.737	0.712
	C	1.776	1.467	1.191	1	1.178	4.724	16.316	25	19.605	7.105	3.303	2.184

Conclusion

Single empirical formula developed for peak flood estimation of various return periods could not be used throughout all basins of Nepal as single probability distribution function may not be a best fit distribution for the hydrological time series data of every station. Different methods are appropriate for different basins. So, basin level study is of utmost importance for the development and identification of accurate and reliable flood computation formulas for each basin. The Rational method, which has overestimated the discharges of various return periods in Bagasoti Gaun has underestimated in Jamu. This corroborates the fact that the same formula might behave differently depending upon the characteristics (size, time of concentration, land use and land cover, etc.,) of various catchments. So, this necessitate the development of suitable flood computation technique that can be used for the estimation of floods of different return period through a basin. Even the same method was unable to estimate the peak flood of different return period for a same catchment as the empirical formulas for peak flood estimation are typically based on statistical relationships between flood peak discharge and other physical characteristics of the watershed, such as drainage area, land use, soil type, and topography. These formulas are developed using historical data from a particular region or watershed. Historical data may not always be representative of future conditions due to climate change, land use changes, and other factors that can affect the frequency and intensity of extreme precipitation events. Therefore, it is essential to update the empirical formulas regularly based on the most recent data and knowledge to ensure their accuracy for different time periods. Reliable estimation of long-term mean monthly flow from limited empirical formulas is also becoming a matter of challenge as not much research focusing on this concern has yet been performed sufficiently.

The number of meteorological stations in Nepal is less than that recommended by the World Meteorological Organization (WMO), and long-term databases for precipitation, land use change, etc. are also hardly available, and this will largely increase our dependence to the empirical formulas for peak flood computation. So, establishment of sufficient number of meteorological and hydrological stations, and abundant research regarding the accurate peak flood and design discharge calculation should be our major focus for impairing devastating effects of flood on life and economy.

In order to develop the rainfall-runoff formula or model, DHM must set up more hydrological stations and recording stations for rainfall. In order to calculate a unit hydrograph from a measured hydrograph, the flow measurements ought to be based on a specific storm. At each station, the regional coefficients of the intensity duration frequency curves should be determined. These studies require DHM to fix similar hydrological zones in Nepal. The consistency of hydrological research conducted by many experts is crucial. Therefore, DHM should have guidelines and rules that every study team would adhere to when estimating the hydrological design parameters.

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