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Estimation of Probable Maximum Precipitation and Probable Maximum Floods Using Synder Unit Hydrograph and HEC-HMS: A Case Study in Kaligandaki River

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Abstract

Highly varied in geological conditions within the short range of reach i.e., about 200 km in widthwise creates a wide range of climatic conditions in Nepal that means high variation in precipitation and flow. The precipitation is highly concentrated in monsoon season where nearly 80 percent of total precipitation occurs. Due to the combination of high relief, steep mountainous landscapes, deep and narrow river valleys and regular mass wasting processes rises the country's susceptibility to natural hazards producing substantial annual damage to property and loss of human lives. Therefore, there is necessity of hydraulic structures to regulate and safely passes the maximum flood happening without damaging. The maximum flood that may be expected is probable maximum flood (PMF) which is developed from the combined effect of extreme metrological and hydrological conditions. PMF is computed by using the probable maximum precipitation (PMP), has physical meanings to provide an engineer for operating and designing the hydraulic structure as upper limit of the interval. Nowadays, PMF is generally taken as the standard value for safety design of hydraulic structures. This research aims to focuses to estimate PMP/PMF at the outlet Ansing of Kaligandaki River by two different methods and analyze the PMFs estimates. Hydro-meteorological method and Statistical method are two methods used to determine the PMPson the basin of outlet. Estimation of PMPs covers the creation of watershed, dividing it into sub basins, finding characteristics of each sub basins from the extension of HEC GeoHMS in ArcGIS 10.2. In hydro-meteorological, basin average PMP is estimated from 1-day maximum PMP contour map and DAD curve whereas annual maximum daily rainfalls are used for PMP estimation in Hershfield method. Snyder unit hydrograph is used as rainfall runoff model to generate the unit hydrograph (UH) at outlets of each sub basin. This UH is convoluted with basin average PMPs to develop the direct runoff hydrograph (DRH). DRH of the flow from every sub basin undergoes routing by HEC-HMS model to estimate PMF at outlet of watershed. HEC HMS model is calibrated and validated at outlets by optimizing its parameters for only routing purpose. Since, the reliability of the PMF relies on the quantity of available data, quality and depth of analysis of PMP estimation, it is essential to analyze, compare and harmonize PMP results from multiple perspectives. Estimated PMFs by statistical is 17.24% more than the estimated PMFs by hydro meteorological method.

Keywords: *PMF, Synder UH Method, Hydro-metrological Method, Statistical Method, Hershfield Method*

1 Introduction

Geographically, Nepal is a landlocked country bordered by China in the north and India on the south, east and west, Nepal is extended from $26^0 22'$ to $30^0 27'$ in latitude and $80^0 4'$ to $88^0 12'$ in longitude having total area 1,47,516 km2 out of which nearly 15 % of Himalayas, 68 % of Hills and 17 % of Terai. The country is lengthwise nearly 880 km from east to west and widthwise nearly 145 to 241 km from south to north (Nepal, 2024). Within this range, there is large variation in altitude ranging from 59 m in southern part (Jhapa, Terai) to 8,848.86 m as Mount Everest in Northern part. Nearly more than 6000 river and rivulets drain from Nepal. The precipitation is highly concentrated in monsoon season where nearly 80 percent of total precipitation occurs. Due to the high concentration of monsoon, rugged terrain, high gradient mountainous. The region is described by rugged topography, deep and narrow river valleys and regular mass wasting events phenomenon manifest the nation more hazardous and losses more property and human life annually. The proper design of hydraulic structure, the designer or planner need the accurate measurement of maximum flow of river. The PMF can be defined as the highest flood that could moderately occur under the most critical combination of meteorological and hydrological conditions(Tiwari, 2025).

PMF is derived from the PMP, has physical meanings to provide an engineer for operating and designing the hydraulic structures as higher range of the interval. The PMP represents the maximum amount of precipitation that can be theoretically appear over a particular area and time duration under most extreme meteorological conditions at that place and season. (Miller, 1986). Different methods are used to determine the PMP at a particular area for a given time periods. The research, two methods are used for estimating are examined: maximization along with transposition of real storms (Hydrometrological approach) as well as Hershfield method (statistical method). A synthetic unit hydrograph is a derived unit hydrograph using an established formula, without a need for analyzing the rainfall-runoff data (Ponce, 2023). One of the most widely applied SUH techniques is Snyder's method**.** Direct Runoff Hydrographs (DRH) can be generated by applying the design storm hyetograph derived from PMP**.** The resulting DRH provides an estimate of the stream flow response, which forms the basis for computing the PMF**.** Hydrological model i.e., HEC-HMS is computer based software is used for the routing the DRHs of each sub basin. After routing DRH in HEC-HMS, Flood hydrograph at outlet of basin is developed. The maximum value of flow in flood hydrograph is PMF of basin at Ansing outlet.

The broad objective of the research is to estimate the PMP as well as PMF at the outlet Ansing of Kaligandaki River by two different methods i.e., Hydrometrological method and statistical method and evaluate extent of variation in PMF estimates. The study estimates PMP in study watersheds using two methods and PMF using the Snyder Unit Hydrograph and HEC-HMS model.

2 Materials and Methods

2.1 Study Area

Figure 1 showed that the current research centers on the computation of PMF at the Ansing gauge station located in the Kaligandaki stream catchment, which is located at the middle region of Nepal, encompassing the districts like Mustang, Myagdi, Parbat, Gulmi, Baglung, and Syanja. This river is a principal tributary of Narayani River Basin. These watersheds cover three Mountain, Siwalik and Terai Physiographic regions of Nepal. Geographically, the river is located between latitude 27°49′43″-29°19′8″ and longitude 83°13'11″-84°15′1″. Its basin has the altitude varying from 340m on the low-lying flood plain to 8120 m. on the ridge. The total catchment area of the Kaligandaki River at Ansing gauge station is 10629.74 km2. The maximum dispersion of precipitation at the basin is found to be 306mm in 7th April, 2022.

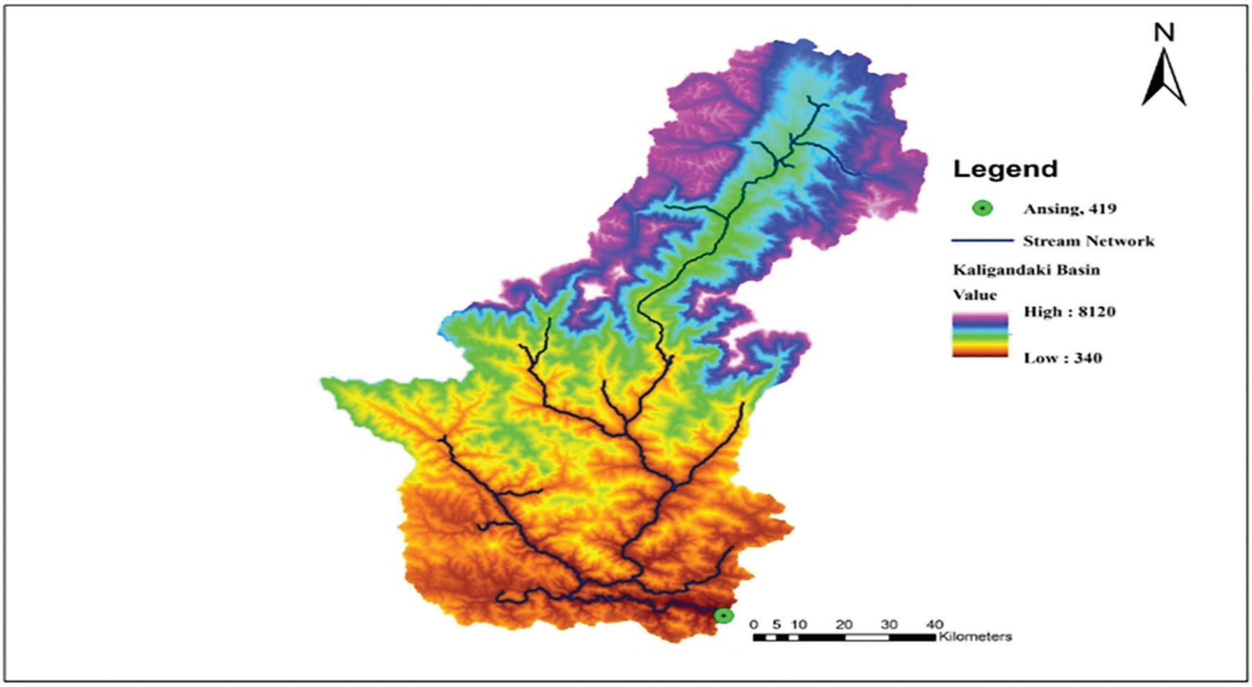

Figure 1: Kaligandaki River Basin of Mustang, Myagdi, Parbat, Gulmi, Baglung and Syanja

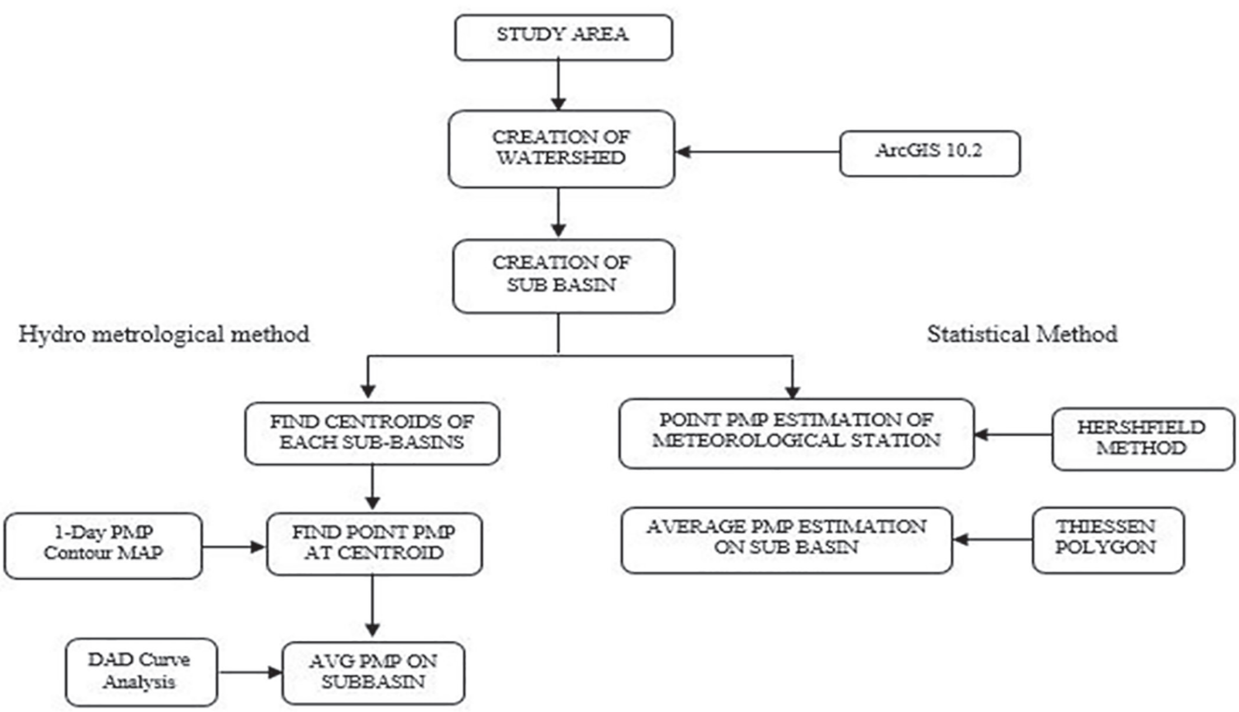

Figure 2: Methodology Framework

2.2 Study Method

The study method adopted to achieve the objectives of this research broadly classified into two steps, i.e., Estimation of PMP and Estimation of PMF. The outlet at Ansing, Kaligandaki (419) is used to elaborate the method adopted for PMF estimation. The PMP is estimated by using hydrometeorological and statistical methods that presented in figure 2.

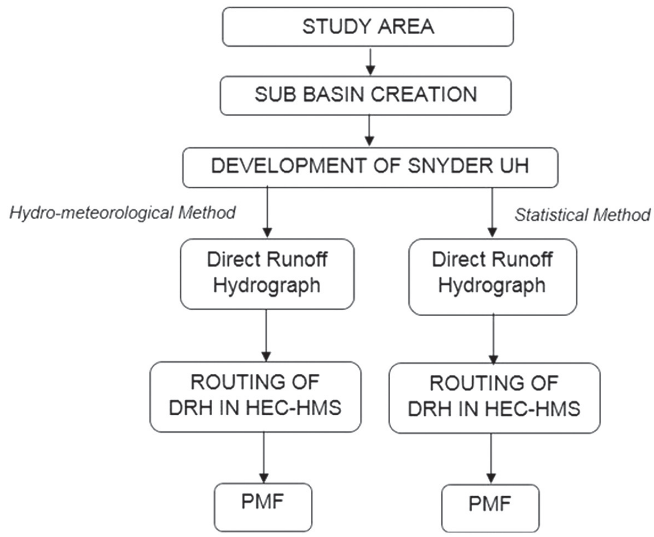

Figure 3: Estimation Work of PMF

Snyder Unit Hydrograph model and HEC-HMS Model are used for the estimation of PMF at required outlet of river basin. A general sequence of works for the estimation of PMP at two different conditions is represented in figure 3 (Mohammed, Al-Manmi, Al-Manmi, & Hamasur, 2023).

2.1.1 Hydrological Model

The rainfall-runoff process is a fundamental mechanism of the hydrological cycle that links precipitation inputs to the resulting stream flow response of a river basin. (Wu, et al., 2025). Based on hydrologic system, there are two major classifications of models like black box lumped model and physically based distributed model (Chow, Maidment & Mays, 1988). Lump models use the catchment as a single catchment and it assumes average parameters considering a single watershed and neglects the effect of routing and transforms mechanism on the development of runoff hydrograph. It is very simplest types of models and provides results very quickly. This type of model cannot give the details behind the flow mechanism (Okiria, et al., 2022).

2.1.2 Description of HEC-HMS Model

HEC-HMS is a computer software developed by the US Army Corps of Engineer that stands for Hydrologic Engineering Center Hydrologic Modeling System. (Wulandari, et al., 2025). HEC-HMS is physically based semi distributed model and mainly used for the hydrological analysis or hydrological simulations. The main application of this model is to flood forecasting, urban area flooding, flood warning system, reservoir simulation etc (Nadeem, et al., 2022). Main aim of HEC-HMS is to develop the relationship between precipitation and runoff within whole basin or sub-basin. To develop this relationship, HEC-HMS utilizes distinct models to simulate the individual parameters of the rainfall-runoff process, including runoff volume, direct runoff, base flow, channel flow as well as cumulative losses example, Green and Ampt loss model (Wulandari, et al., 2025). Green Ampt model is used as loss model to simulate the infiltration water from the surface of land to sub-surface (Khanaum & Borhan, 2023). This model assumes the water initially uniformly distributed throughout the soil surface and water starts to infiltrate into soil from initial condition of soil to perfect saturated soil (Zhu, et al., 2025). Governing equation used in HEC-HMS for governing loss by Green-Ampt methods are presented in equation 1.

$$f_t = K \times \left[\frac{1+(\phi-\theta_i)*S_f}{F_t}\right] \tag{1}$$

Where, ft = Infiltrated water in time t K= Saturated hydraulic conductivity (ϕ-θi) = Moisture volume deficit Sf = Wetting suction font Ft = Cumulative loss in time t

The Muskingum method is developed by McCarthy in 1938 for the estimation of flow hydrograph by establishment of channel routing technique. The technique of channel routing is under the assumption of linear among inflow, storage as well as outflow of river. It assumes the water body like a wedge prism. The Muskingum approach depends on the differential equation of storage are presented in equation 2 and 3 (Salvati, et al., 2024).

$$I - o = \frac{ds}{dt} \tag{2}$$

$$\frac{1}{2}(I_1 + I_2) - \frac{1}{2}(O_1 + O_2) = \frac{S_1 - S_2}{\Delta t} \tag{3}$$

Where, S is again related as presented in equation 4,

$$S = K[XI + (1 - X)O] \tag{4}$$

Here, X is weightage factor, 0 ≤ X ≥ 0.5 and K is obtained from equation 5.

$$\frac{ds}{dt} = \frac{S^{j+1} - S^j}{\Delta t^j} = K\left[\frac{(XI^{j+1} + (1-X)O^{j+1}) - (XI^j + (1-X)O^j)}{\Delta t^j}\right] \tag{5}$$

Where, j and j+1 represent value of different time separated by the interval Δt.

For the outflow of the reach, we get the relation of out flow as,

$$O^{j+1} = C_1 I^{j+1} + C_2 I^j + C_3 O^j \tag{6}$$

Equation 6 is the Muskingum Routing equation, where value of C_1, C_2 and C_3 are taken from equation 7, 8 and 9.

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} \tag{7}$$

$$C_1 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \tag{8}$$

$$C_1 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t} \tag{9}$$

Such that,

C1+C2+C3=1

K/3 ≤ Δt ≤ K, where the value of K taken from equation 10

$$K = \frac{0.5\Delta t\left[I^{j+1}+I^{j}-\left(O^{j+1}+O^{j}\right)\right]}{X\left(I^{j+1}+I^{j}\right)+(1-X)\left(O^{j+1}+O^{j}\right)} \tag{10}$$

2.2 Extracting Physical Characteristics of watershed using HEC-GeoHMS

ArcGIS software is computer-based program, developed by Environmental Systems Research Institute (ESRI) and used for getting geospatial information by the analysis of spatial data. Using it, vector data or simply shape files and raster dataset can be observed and edited. ArcGIS has various inbuilt extensions used for Spatial Analyst, Network Analyst, Geostatistical Analyst and more. Apart from these inbuilt extensions ArcGIS also includes other extensions like ArcHydro, ArcSWAT, ArcSCAN, HEC-GeoRAS, HEC-GeoHMS and many more that makes analysis of data easier and faster. It enables the visualization of spatial data, extraction of watershed characteristics from DEM (Digital Elevation Model) along with GIS datasets, performing spatial analysis, delineating sub basins and river networks as well as generating hydrologic parameters required for hydrologic simulations. (Marketing, 2020).

2.3 Methods for Estimating Probable Maximum Precipitation (PMP)

The PMP can be defined as the greatest depth of precipitation that is theoretically occurred over a specified duration over a specified storm area of a given size at a particular geographic location at a given time of year. (Kim, Kim, & Tachikawa, 2024). Hydro-meterological method and Statistical method are used to estimate the PMP.

Hydrometrological method (Moisture Maximization Method)

i. Estimation of Point PMP:

This method involves maximizing the meteorological factors governing convective precipitation, particularly the moisture contents present in the atmosphere or precipitable water by estimating the maximum possible abundant precipitable water within the air column above the located site or grid location are presented in equation 11 (Chavana & Srinivas, 2015).

$$PMP = \frac{W_m}{W} P \tag{11}$$

Where, PMP in mm, P= Observed Precipitation depth in mm, W= Precipitable water in air column above the target site during storm, Wm= Maximum precipitable water in air column and W can be estimated based on equation 12 (Chavana & Srinivas, 2015).

$$Ln(W) = 0.1133 - Ln(\lambda + 1) + 0.0393T_d \tag{12}$$

λ=The exponent in power law that defines the relationship between the moisture profile and the height of atmospheric column and depends on latitude of focused site and storm occurring season of the year, T_d = temperature of Surface dew point (^{0}F) corresponds to recorded maximum surface temperature on stormy day and can be estimated from equation 13, when T_d are not available (Chavana & Srinivas, 2015).

$$T_d = \frac{237.3\ln(R_h)+237.3\left(\frac{17.27T}{237.3+T}\right)}{17.27-\ln(R_h)-\left(\frac{17.27T}{237.3+T}\right)} \tag{13}$$

Where, R_h = Relative humidity, T= Maximum surface temperature(^{0}C) corresponds to stormy day and W_m can be estimated based on equation 14 (Chavana & Srinivas, 2015).

$$Ln(W_m) = 0.1133 - Ln(\lambda + 1) + 0.0393T_d^{max} \quad (14)$$

When the historical recorded value of Td extends for 50 years or more then Tdmax is taken as the highest of recorded Td value for the month during which storm occurred, otherwise, Tdmax is estimated as 100 year return period obtained from historical monthly maximum Td values corresponding to storm month (WMO, 1986).

ii. Estimation of average PMP over basin:

Depth Area Duration (DAD) Analysis

The primary objective of a DAD analysis for a specific storm is to determine the maximum average rainfall depth occurring over different catchment areas and standard durations (hours or days), such as the highest rainfall depth over 1000 km² within 24 hours; these values are essential for identifying the most severe storm events and for providing the fundamental data required to estimate the PMP of a basin (Othman, Manshor, & Samat, 2022). The areal distribution characteristics of a storm of a given duration is govern by equation 15 (Subramanya, 2013):

$$P = P_o exp^{(-KA^n)} \quad (15)$$

Where, P= Average storm depth in cm over an area, Po = Maximum rainfall depth in cm at middle, K and n are the constant for given basin.

Statistical method

Statistical method, Hershfield approach is used when long term precipitation data is sufficient. Hershfield used the parameters like mean, standard deviation and frequency factor for the chain of yearly maximum rainfall and can be estimated using equation 16 (Subramanya, 2013):

$$X_m = X_n + K_m * S_n \quad (16)$$

Where, X_m= Maximum rainfall, X_n= mean of chain of n yearly maximal 24-hours rainfall, S_n= standard deviation of a chain of n yearly maximal 24-hours rainfall, K_n= statistical variable.

Analysis of thousands of rainfall station-years have shown that multiplying the yearly maximum rainfall values extracted from frequency analysis for a given duration between 1 and 24 hours by a factor of 1.13 gives an estimate of the maximum rainfall values presented in equation 17.

$$Adjusted\ PMP = 1.13 * PMP \quad (17)$$

2.4 Establishment of Synder Unit Hydrograph (SUH)

The Snyder Unit Hydrograph, developed by F. F. Snyder in 1938, is an empirical method widely used for ungauged catchments, where hydrograph parameters such as time to peak, watershed area, longest flow path, and centroidal flow path are used to estimate peak discharge and runoff characteristics based on analyses of numerous drainage basins ranging from 25 km² to 25,000 km². Snyder describes the lag time (T_p), peak discharge (Q_p) and total base time (T_b) as the major characteristics of a Snyder UH are presented in equation 18 (Chow, Maidment, & Mays, 1988).

$$T_p = C_1 * C_t * (L * L_c)^{0.3} \quad (18)$$

For standard Unit Hydrograph; ($T_R = T_r$ *and* $T_p = T_{pR}$) are presented in equation 19, 20 and 21.

$$T_r = \frac{T_p}{5.5} \tag{19}$$

$$Q_p = \frac{C_2 * C_p * A}{T_p} \tag{20}$$

$$T_b = \frac{C_3 * A}{Q_p} \tag{21}$$

Required Unit Hydrograph; ($T_R \neq T_r$, $T_p \neq T_{pR}$ and $T_{pR} \neq 5.5 * T_R$) are presented in equation 22, 23, 24 and 25.

$$T_{pR} = T_p - (T_r - T_R)/4 \tag{22}$$

$$Q_{pR} = Q_p * \frac{T_p}{T_{pR}} \tag{23}$$

$$T_b = \frac{C_3 * A}{Q_{pR}} \tag{24}$$

$$W = C_w * (\frac{Q_{pR}}{A})^{-1.08} \tag{25}$$

2.5 Methods for Estimating Probable Maximum Flood (PMF)

The PMF represents the flood that is expected to come from the most critical combination of meteorological and hydrological conditions (Tiwari, 2025). The PMF is computed from the PMP, has physical meanings to provide an engineer for operating and designing the hydraulic structure as higher range of interval. So, the calculation as well as prediction of PMF is a main subject in hydrologic engineering as well as for the safety of hydraulic structures (Tiwari, 2025). The PMF is estimated after the development of the DRH, where DRH is obtained by the UH with the average PMP. For large river basins with catchment areas exceeding 5000 km^2, the basin is subdivided into several sub-basins, and the average PMP along with the Snyder Unit Hydrograph is determined individually for each sub-basin (Bantchina & Gündoğdu, 2021). Subsequently, DRHs are generated by convoluting the Unit Hydrograph with the corresponding average PMP values. The DRHs of individual sub-basins are then routed using the HEC-HMS model for PMF estimation are presented in equation 26 (Subramanya, 2013).

*[Ordinate of DRH of each sub-basin] = [Ordinate of UH*Average PMP + Base flow]* (26)

3 Result and Discussion

3.1 Estimation of Probable Maximum Precipitation (PMP)

The PMP is estimated by using hydro-meteorological and Hershfield methods are presented in figure 4.

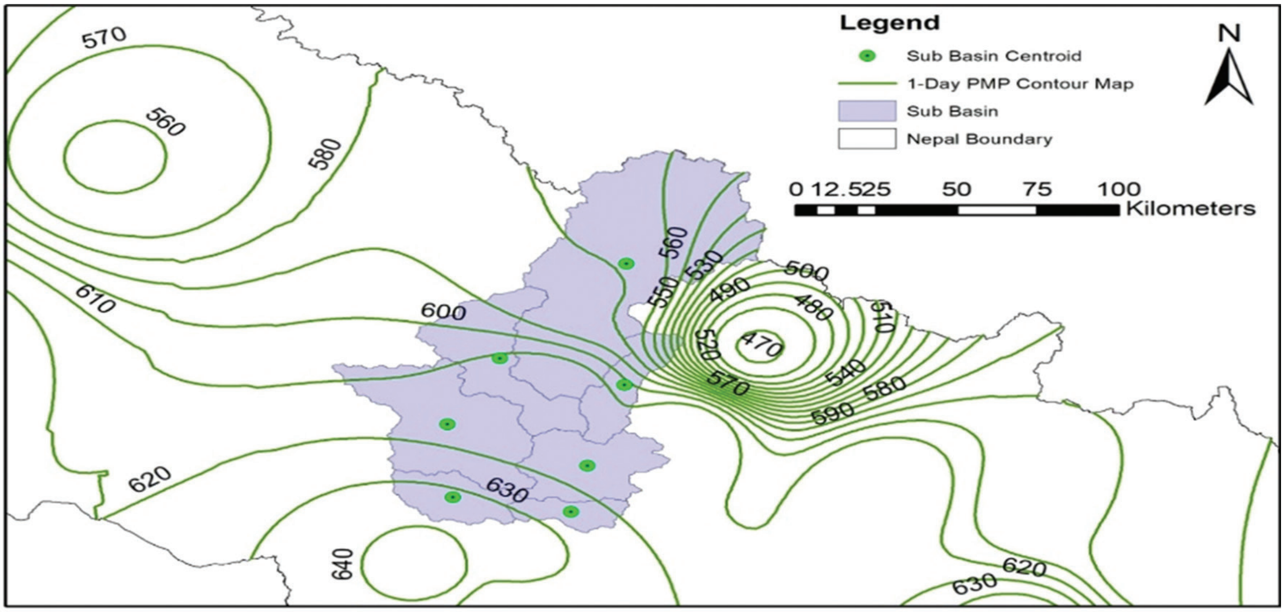

Figure 4: PMP at Centroid of Sub Basin

3.1.1 Hydro-meteorological method

This approach is generally generally referred by the World meteorological organization (WMO). In this approach, the watershed for the given outlet is created using ArcGIS 10.2. The watershed is sub-divided into the seven numbers of sub basin using the HEC-HMS as the extension of ArcGIS 10.2. The maximized point PMP at the centroid of sub basin is estimated using 1-day PMP counter map. The maximized point PMP is then distributed to sub basin using DAD curve (Puji, Agriamah, Riawan, Suwarman, & Lubis, 2021).

i) 1-Day PMP Contour Map

1-Day PMP Contour Map represents the line joining of equal PMP value distributed over the region of Nepal. PMP values are estimated by Hydrometrological method i.e., moisture maximization and storm transposition that presented in figure 5.

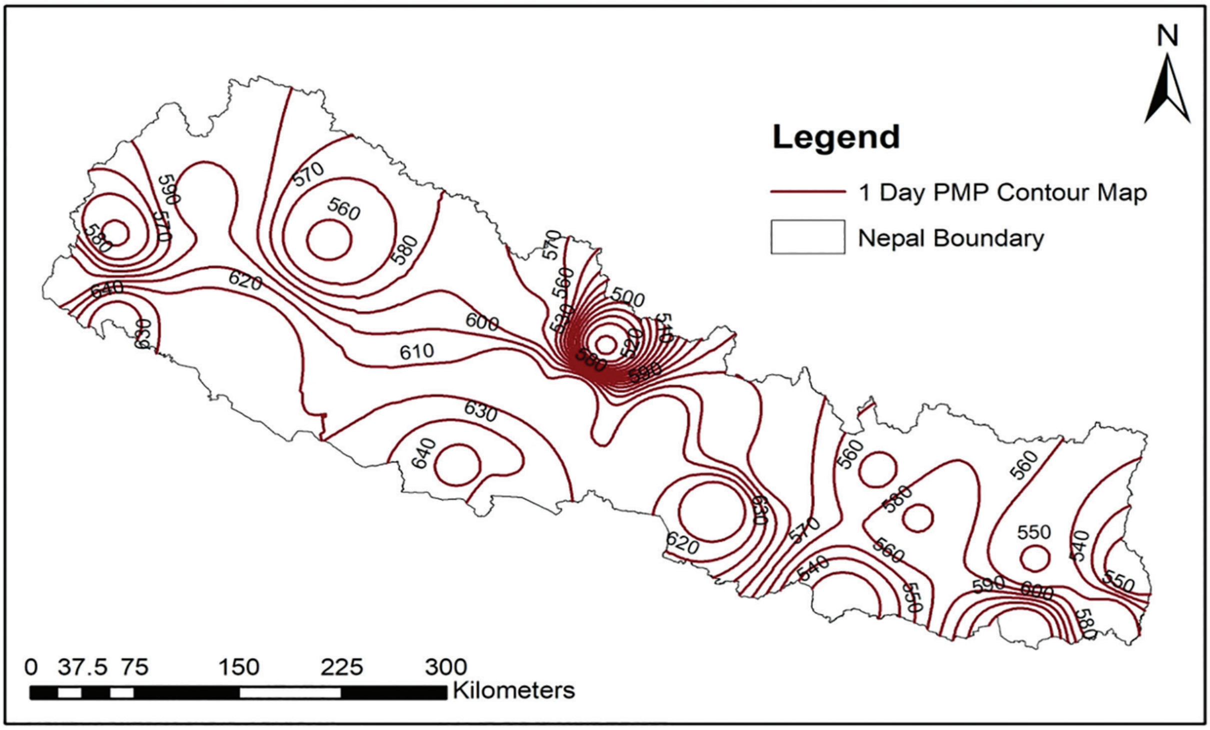

Figure 5: Day PMP Contour Map

ii) DAD Curve

Depth area duration curve shows fixed relation between the depth, area and duration of rainfall. The immediate goal of a DAD analysis of a given storm is used to estimate the greatest average depth of precipitation over a various size of area. The DAD analysis is carried out either by the mass curve approach or by the incremental iso-hyetal approach depending upon the manner of portraying the time division of rainfall. In our study, we used incremental isohyetal method are given in table 1 and figure 6.

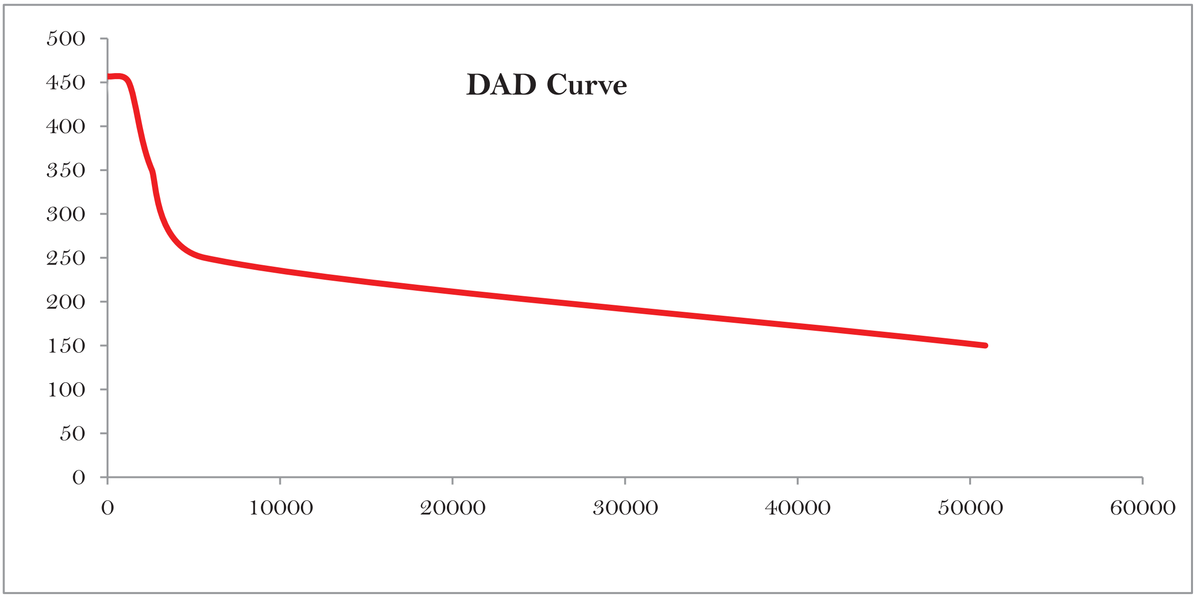

Figure 6: DAD Curve of 1-day Maximum Storm

Table 1: Area enclosed and corresponding depth of 1-day PMP

Area (sq.km)	Depth (mm)
0	456.8
1229	450
2568	350
5631	250
50878	150
922714	50

3.1.2 Statistical method

Hershfield (1961, 1965) was applied for the estimation of average PMP on each sub basins of the catchment are presented in equation 27 (Daba, Demissie, & Sime, 2021).

$$x_t = \bar{x}_n + k_m s_n \quad (27)$$

From the observed precipitation data (from 1993 to 2019), mean (x_n), standard deviation (s_n) and maximum values (x_m) of each metrological station are estimated. In addition, mean (x_{n-m}) and standard deviations (s_{n-m}) are calculated after excluding that maximum precipitation value. The value of k_m is estimated from the Nomograms of Hershfield, 1961b. Analysis of thousands of rainfall station- years have shown that multiplying the yearly maximum rainfall values extracted from frequency analysis for a given duration between 1 and 24 hours by a factor of 1.13 gives an estimate of the maximum rainfall amount (Daba, Demissie, & Sime, 2021). The average PMP for every sub basin is determined by utilizing the Thiessen polygon approach. The Hershfield method is applied considering the observation on daily precipitation value of 38 metrological stations for Kaligandaki river basin over the period 1956 to 2019. Estimation of 1-day PMP of 1-day was estimated corresponding to each grid point. Estimated 1-day PMP value is adjusted by multiplying the adjustment factor 1.13. Using Thiessen Polygon method, the average PMP in each sub basin was calculated. The significant spatial heterogeneity over entire basin ranges from 449.89mm (sub basin-1) to 1069.2mm (sub basin-7) was shown by estimated PMP and are presented in table 2 and figure 7.

Table 2: Estimated average PMP on Sub Basin

Sub basin	1	2	3	4	5	6	7
Area of Basin (sq.km.)	4538.2	1357.9	675.1	1060.8	2000.5	633.2	363.7
Hydrometrological method							
Historical Maximum Storm PPT (mm)	456.8	456.8	456.8	456.8	456.8	456.8	456.8
Maximized Point PMP (mm)	545	640	605	630	640	628	640
DAD Factor	1.19	1.40	1.32	1.38	1.40	1.37	1.40
Average PMP (mm)	442.70	628.10	600.50	625.30	606.40	623.30	635.20
Statistical Method, mm							
Average PMP (mm)	449.89	608.81	787.99	927.73	724.58	1038.01	1069.22

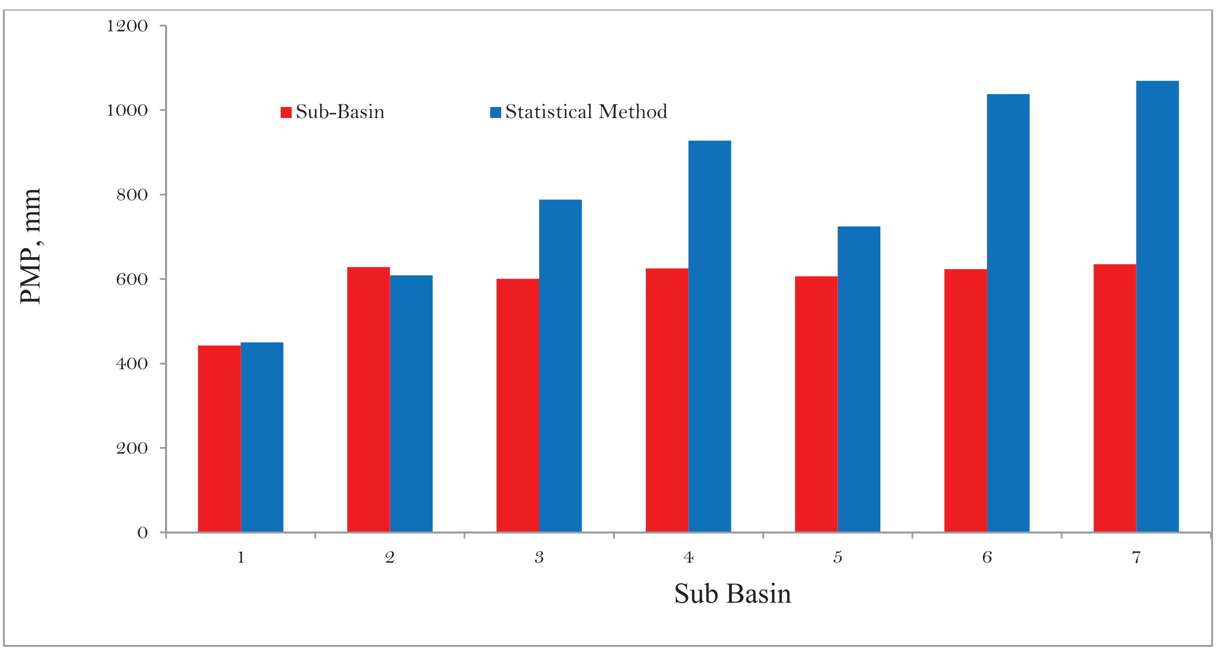

Figure 7: Comparison of PMPs at Kaligandaki River Basin

3.2 Snyder UH and Direct Runoff Hydrograph

As discussed in methodology, River basin is sub divided into seven sub basins having different area ranges from 363.77 km^2 to 4538.20 km^2. The altitude of basin between 8120 m to 340 m from masl. Snyder UH parameters such as basin lag time, high discharge, time of peak, base time. The widths corresponding to 50%(W50) and 75%(W75) of the peak discharge are calculated using physiographic parameters. The analysis of Snyder UH peak estimation reveals that the peak discharge increases as the standard lag time decreases and it also increases as the watershed areas increase. River basin response time depend upon sub basin area and river length i.e., smaller area and river length quick response time. Sub basin 1 has largest area of 4538.20 km^2, longest river length of 159860 m, peak discharge of 139.50 m^3/s and time of peak as 39 hr whereas Sub basin 7 has smallest area of 363.77 km^2, longest river length of 57180 m, peak discharge of 16.40 m^3/s and time of peak as 24 hr. The UH for seven sub basins are presented in table 3.

Table 3: Physical Properties of sub basin

Basin	1	2	3	4	5	6	7
Area<5000m (Sq.km)	4538.20	1357.99	675.11	1060.86	2000.54	633.27	363.77
Longest Flow Length (L, m)	159860	81721	64187	81175.0	95243	63400	57180
Centroidal Flow Length (L_{ca},m)	82354	62700	31701	47502	45362	28804	21231
Channel Slope (s)	0.0364	0.0694	0.1130	0.0239	0.0320	0.0254	0.0204
Time of Peak (hr)	39	30	27	30	30	24	24
Peaks of Snyder UH (m^3/s)	139.50	53.10	29.30	41.30	75.30	28.50	16.40

The established unit hydrograph ordinates were utilized to derive the DRH for each sub-basin based on the estimated average PMP obtained from both the Hydrometrological and Hershfield methods. This process involved multiplying the unit hydrograph ordinates by the estimated average PMP. The base flow for each sub-basin was determined by proportionally distributing the observed base flow at the Ansing outlet according to the respective sub-basin areas. The resulting DRHs for the seven sub-basins derived from both methods. The Hydrometrological method produced minimum and maximum DRH values of 1044.60 m^3/s (Sub-basin 7) and 6215.80 m^3/s (Sub-basin 1), respectively while the Hershfield method yielded corresponding values of 1756.10 m^3/s (Sub-basin 7) and 6313.60 m^3/s (Sub-basin 1). The difference in the estimated DRH discharge at the sub-basin outlets is more pronounced in smaller sub-basins, whereas the values are relatively comparable in larger sub-basins. The percentage difference ranges from 2% in Sub-basin 1 to 68% in Sub-basin 7. Table 4 and figure 8 illustrates the variation in discharge with respect to sub-basin size.

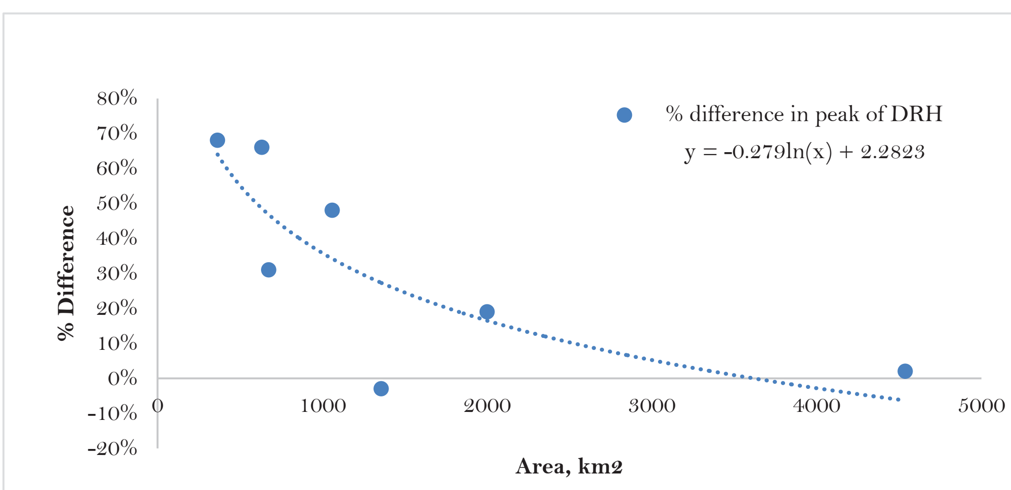

Figure 8: Graphical representation of percentage variation in peaks of DRH with respect to basin sizes

Table 4: Discharge Variation with Respect to Sub-Basin Size

Basin	1	2	3	4	5	6	7
Area<5000m (Sq.km)	4538.20	1357.99	675.11	1060.86	2000.54	633.27	363.77
Base Flow, m^3/s	38.40	11.50	5.70	9.00	16.90	5.40	3.10
Peak of DRH, m^3/s (Hydrometrological, PMP)	6215.80	3344.00	1767.00	2592.90	4583.80	1784.40	1044.60
Peak of DRH, m^3/s (Hershfield, PMP)	6313.60	3241.50	2316.90	3842.50	5474.00	2968.00	1756.10

3.3 Estimation of Probable Maximum Flood (PMF)

The Snyder's method was used to evaluate the characteristics of the unit hydrograph, including lag time or basin lag (Tp), unit-hydrograph duration (Tr), peak discharge (Qp), time base or base period (Tb). The identification of all these parameters facilitates the creation of unit hydrographs. The DRH is developed after convoluting the unit hydrograph with storm PMPs are presented in equation 28.

$$[\text{Ordinate of DRH}] = [\text{Ordinate of UH*Average PMP + Base flow}] \tag{28}$$

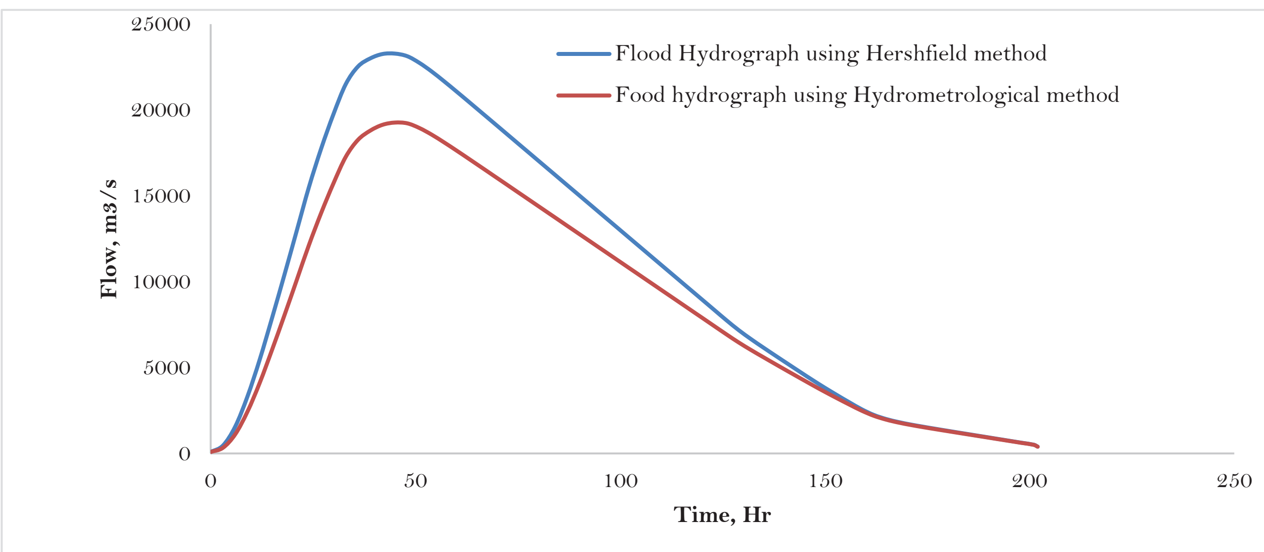

Figure 9: Performance characteristics of river basin for calibration and Validation of hydrological model

HEC-HMS model is used for the routing the DRHs of each sub basin. For routing DRH, HEC-HMS model is calibrated and validated using the optimizing parameters. DRH of each sub basin is input of model. After routing DRH in HEC-HMS, Flood hydrograph at outlet of basin is developed. This framework included the basin model, metrological model, control specifications and time series data are four major model ingredients of HEC-HMS model. The parameter selected in model are simple canopy, simple surface, Green and Ampt loss, Snyder UH transform and Muskingum as routing. The HEC-HMS modeling software was employed to route the estimated DRHs obtained at the outlets of each sub-basin. Observed discharge data from 1995 to 2004 were used for calculation while data from 2004 to 2009 were utilized for validation. Model performance statistics indicated satisfactory agreement, with NSE, RSR, and PBIAS values of 0.78, 0.50, and 10.25% for calibration, and 0.84, 0.40, and 7.21% for validation, respectively. The DRHs served as inflow hydrographs in HEC-HMS to generate the corresponding maximum outflow hydrographs. The analysis revealed peak discharges of 19,266.60 m^3/s for the Hydrometrological method and 23,281.20 m^3/s for the Hershfield method that presented in figure 9.

4 Conclusions

This research aims to analyze the possible 1-day PMP and corresponding PMF at the Ansing outlet of Kaligandaki river basin. Probable maximum flood for 1-day PMP using both Hydrometrological and Hershfield method in Kaligandaki river basin in this paper presents very effective in planning, designing and management of various hydraulic structures empowering the optimal utilization of water resources within the basin. Such studies are especially important for river basins aligned in highly orographic regions where multiple rain bearing weather systems interact and generate complex precipitation patterns affect the basin. The whole river basin is divided in seven number of sub basin with varying basin sizes to analyze the maximum flood level at different point within basin. Estimated PMP using both Hydrometrological and Hershfield method is applied in Snyder UH method to generate the DRH at the outlet of each sub basins. The peaks of DRH gives the maximum flood level for designing the different civil structures. Also, peak value of flood hydrograph at Ansing outlet which is generated by routing DRHs using HECHMS in both cases gives the PMF. This study analyzed the 1-day PMP and the corresponding PMF at the Ansing outlet of the Kaligandaki River basin. PMP was estimated using both the hydro-meteorological and Hershfield methods, and applied through the Snyder unit hydrograph to generate DRHs for across the seven sub basins. Routing of these DRHs in HEC-HMS provided the peak flood hydrograph at the Ansing outlet, representing the PMF. The results highlight that such assessments are essential for planning, design, operation and management of hydraulic structures to ensure the optimum utilization of water resources, particularly in highly orographic basins influenced by multiple rain-bearing systems. While statistical methods are useful for rapid estimation when only precipitation data are available, the hydro-meteorological method offers more reliable and physically consistent results when detailed meteorological records are accessible.

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