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Estimation of Probable Maximum Flood for a Water Resource Development Project in Upper Narmada Basin

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Abstract*— Estimation of probable maximum floods (PMF) is essential for design of spillways and various water resource development projects. Depending on various assumptions and approaches, resulting PMF estimates may vary differently. Recently, Probable Maximum Precipitation (PMP) Atlas of various basins of India has been prepared jointly by Central Water Commission and India Meteorological Department, Government of India. This paper uses the grid wise PMPs given in the Atlas to estimate PMF hydrograph of at project site in Narmada River. The catchment area is divided into four sub catchments and unit hydrographs for each sub catchment are derived from the physiographic characteristics. A hydrologic model is setup in HEC-HMS 3.5 for estimating flood hydrographs at outlet of each sub catchment and finally at the project site by hydrologic flood routing approach.

Keywords—Probable maximum flood (PMF), catchment characteristics, Unit hydrograph, hydrologic routing, HEC-HMS

I. INTRODUCTION

Surface runoff estimation is of utmost importance for the hydrologic study of a watershed since it helps in quantifying discharge at its outlet for the construction of different hydraulic structures like dams, embankments etc. Also, the threatening climate change demands the precise and correct estimation of future water availability for different socio-economic needs of the region as well as for natural disasters like floods. Designs of most major dams and spillways are based on probable maximum floods (PMF). When properly estimated, PMFs provide the basis for confident sizing of spillway. There are, however, many factors which affect estimation of PMF. In analyzing each of these factors, certain assumptions have to be made and subjective judgments exercised. Depending on these assumptions and judgements, resulting PMF estimates may be quite different. Wang (1987) provides a brief summary of various International practices in PMF estimation and application, and offers some guidelines for such practices. For the Inflow Design Flood (IDF) of a structure, Bureau of Indian standard guidelines IS: 5477 (Part IV) recommend any of the following type of floods may be chosen from Probable maximum Flood (PMF), Standard Project Flood (SPF) or Flood of a specific return period depending on the intensity of risk involved for life and property. The present study involves computation of PMF which is required in the design of large dams (hydraulic head greater than 30 m). PMF results from the most severe combination of critical meteorological and hydrological conditions that have a very rare chance to occur. Probable Maximum Storm (PMS) which denotes the physical upper limit of storm rainfall helps in computation of PMF over the catchment.

The HEC HMS model generates the surface runoff response of a basin to precipitation, primarily applicable to flood estimation. HEC-HMS comprises of three processes; the loss, the transform and the base flow for any basin modelling. Computation of stream flow hydrographs and PMF for individual sub basins and at the basin outlet are the primary results of this modelling process. HEC-HMS hydrological model has been popular for a long time among hydrologists and researchers like Majidi and Shahedi (2012) and Arekhi et al. (2011) to simulate rainfall-runoff process and compare the different methods of precipitation loss Constant loss, Initial and constant loss rate, Deficit and Green & Ampt. Also, Radmanesh et al (2006) and Momcilo et al (2007) applied HEC-HMS used the HEC-HMS to simulate the rainfall runoff process in their study areas on Yellow river, south western Iran and in northeastern Illinois to study changes pertaining to peak flow caused by increase in precipitation at 12 stations using daily rain-fall data, respectively.

II. STUDY AREA AND DATA AVAILABILITY

Bargi (Rani Avanti Bai Sagar Project) is one of the major masonry earth schemes in the head reaches of Narmada River. This project comprises of the Bargi dam on the Narmada River near village Bargi in the Jabalpur district 43 km away from Jabalpur city. The latitude and longitude of the dam are 22° 56’ 30" N and 79° 55’ 30" E, respectively. The area of the catchment up to the outlet (Bargi) is about 14,584 km^2 and the average annual rainfall in the catchment is 1,414 mm. The SRTM DEM (Fig.1) is downloaded for delineation of sub basins and estimation of catchment characteristics. The gridded PMP values are obtained from PMP atlas (CWC, 2015).

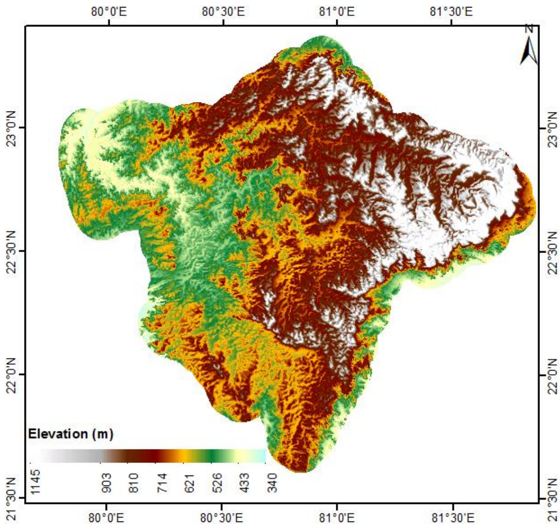

Figure 1: SRTM DEM of the study area

III. METHODOLOGY

A. Catchment Delineation and estimation of physiographic characteristics

The SRTM DEM is used for catchment delineation in Arc GIS with help of ArcHydro tools. The study area is divided in to four sub catchments. The various physiographic parameters like area of the catchment, length, centroidal length, slope, river length and river slope of the four sub catchments are computed in GIS platform.

B. Derivation of Synthetic Unit Hydrograph (SUH)

The various parameters of the synthetic unit hydrograph are derived from the Flood Estimation Report (CWC, 2002). Detail description of the parameters and their relationships are given in Table 1. The 1 hr synthetic unit hydrograph is generated using these SUH parameters and checked for its volume with the help of guidelines provided in the report.

Table 1: Various SUG Parameters (CWC report 2002)

Sl. No.	Parameters	Relationship
1	Time in hours from the centre of unit rain fall duration to the peak of unit hydrograph	$t_p = 0.995\left(LL_c/\sqrt{S}\right)^{0.2654}$
2	Peak discharge of unit hydrograph per unit area of catchment (m^3/s/ km^2)	$q_p = 1.665\left(t_p\right)^{-0.71678}$
3	Width of UH in hours at 50 percent of peak discharge	$W_{50} = 1.9145\left(q_p\right)^{-1.2582}$
4	Width of UH in hours at 75 percent of peak discharge	$W_{75} = 1.1102\left(q_p\right)^{-1.2088}$
5	Width of the rising limb of UH in hours at 50 percent peak discharge	$WR_{50} = 0.706\left(q_p\right)^{-1.3859}$
6	Width of the rising limb of UH in hours at 75 percent peak discharge	$WR_{75} = 0.45314\left(q_p\right)^{-1.3916}$
7	Base width of unit hydrograph in hours	$T_B = 5.04537\left(t_p\right)^{0.71637}$
8	Peak discharge of unit hydrograph in m^3/s	$Q_p = q_p \times A$

Where, L = Length of the main stream (km), S = Equivalent stream slope (m/km), A= Area of the catchment (km^2)

C. Estimation of Probable Maximum Precipitation (PMP)

There are two approaches to compute PMP. The physical or meteorological approach, demands identification of the maximum rainfall generated by severe rainstorms over a catchment and neighbouring areas. Severe storm database leads to the process of PMP estimation after working out Depth Area Duration (DAD), Depth Duration (DD), envelope/transposed depth, their temporal and areal distribution, and moisture adjustment parameters. The other one is statistical approach where the estimates of PMP at a particular location are determined from the frequency analysis of annual maximum rainfall data. This method is quite helpful in handling large amount of data used and where there is no scope of moisture maximization. In this study PMP values are estimated from the PMP Atlas for Narmada, Tapi, Sabarmati, and Luni River Systems and Rivers of Saurashtra and Kutch Regions including Mahi, prepared jointly by Central Water Commission and India Meteorological Department, Government of India. These are ideally suited for projects on medium size river basins with a drainage area matching with one of the standard areas adopted in the atlas with further restriction that the project basin should have one of the grid points close to its centre. In this case, we need to pick up suitable areal PMP values surrounding the sub basin such that we take the average of all the PMP values at the grid points after interpolating the values at individual grid points for specified catchment areas. The PMPs calculated by averaging the PMPs at different grid points surrounding a sub basin and interpolating it for the areas of the four sub basins as shown in Fig. 2. The 1 day PMP is distributed to hourly incremental rainfall with help of different time distribution coefficients.

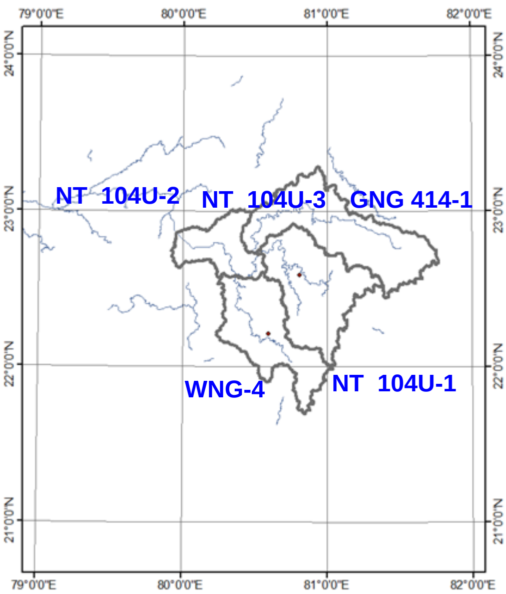

Figure 2: Grid numbers surrounding the sub basins obtained from the PMP atlas

D. Estimation of PMF using HEC-HMS

The HEC-HMS can be used to simulate a single watershed or a system of multiple hydrologically connected watersheds. The first step in the application of HEC-HMS is defining the basin area and sub-basins, a stream network, and diversions and junctions. Like any physically-based hydrologic model, HEC-HMS simulates most of the key hydrologic processes at watershed scale.The HEC-HMS model is prepared for the study area with four sub basins and two reaches as shown in Fig. 3. Various inputs parameters viz. catchment area, loss method, base flow method, transform method etc. are provided as inputs. The initial and constant loss method, user specified unit hydrograph method (synthetic unit hydrograph with CWC parameters) account for the loss and transform method respectively. The various parameters for hydrologic routing of the two reaches are given in Table 2.

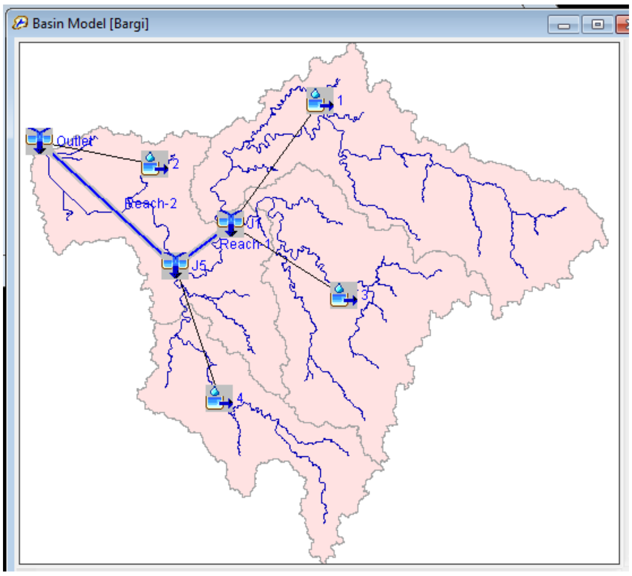

Figure 3: HEC-HMS setup for the study area

Table 2: Various parameters of the two reaches

Reach No.	Length (m)	Width (m)	Equivalent Slope (m/m)
1	40250	150	0.00015
2	88682.8	450	0.00028

IV. Results And Discussions

A. Synthetic Unit Hydrographs

The various physiographic parameters estimated for four sub basins are given in Table 3: Using these Physiographic Characteristics and relationships provide in Table 1, the parameters of synthetic unit hydrographs are estimated as given in Table 4 and the developed SUHs are shown in Figure 4.

Table 3: Physiographic Characteristics of the sub basins

Sub basin No.	Catchment Area (A) (km^2)	Length (L) (Km)	Centroidal Longest Flow path(L_c) (Km)	Equivalent Slope (m/Km)
1	4925.02	271.6	162.38	1.95
2	1911.54	119.89	45.1	1.501
3	4235.7	189.7	101.87	2.39
4	3511.88	189.63	95.19	1.37

Table 4: SUG Parameters of the four sub basins

Parameters	Catchment 1	Catchment 2	Catchment 3	Catchment 4
Time in hours from the centre of unit rain fall duration to the peak of unit hydrograph	15.6	9.3	12.2	12.9
Peak discharge of unit hydrograph per unit area of catchment ($m^3/s/ km^2$)	0.24	0.34	0.28	0.27
Width of UH in hours at 50 percent of peak discharge	11.54	7.44	9.5	9.95
Width of UH in hours at 75 percent of peak discharge	6.24	4.1	5.18	5.41
Width of the rising limb of UH in hours at 50 percent peak discharge	5.11	3.15	4.13	4.34
Width of the rising limb of UH in hours at 75 percent peak discharge	3.31	2.04	2.67	2.81
Base width of unit hydrograph in hours	36.11	24.93	30.28	31.52
Peak discharge of unit hydrograph in m^3/s	1182	650	1186	948

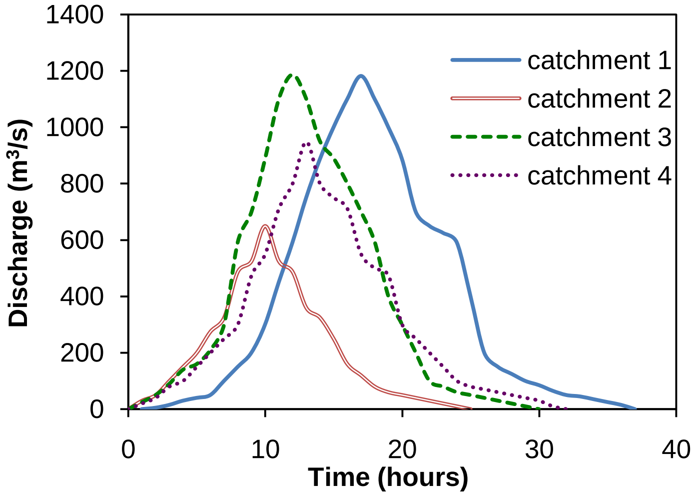

Figure 4: SUHs for the four sub basins

B. PMF Estimation

All the necessary data are provided in HEC-HMS model to carry out simulation. The estimated 1day PMP values are 40.20 cm, 43.91 cm, 40.57 cm and 43.23 cm for the catchments 1, 2, 3 and 4 respectively. These values are converted into hourly value and arranged for critical sequence. Constant base flow is also provided. The resulting PMF hydrograph with hourly rainfall for the four sub catchments are shown in Figure 5. The peak discharges as simulated by HEC-HMS for the four sub basins are 27876.3 m^3/s, 13942.7 m^3/s, 26424.9 m^3/s and 22247 m^3/s respectively for the sub basin-1, sub basin-2, sub basin-3 and sub basin-4 respectively. The generated PMF hydrographs are routed through the two reaches to estimated required PFM hydrograph at the project site as shown in Figure 5. The peak of probable maximum flood for the whole watershed at the outlet is estimated to be77772.6 m^3/s.

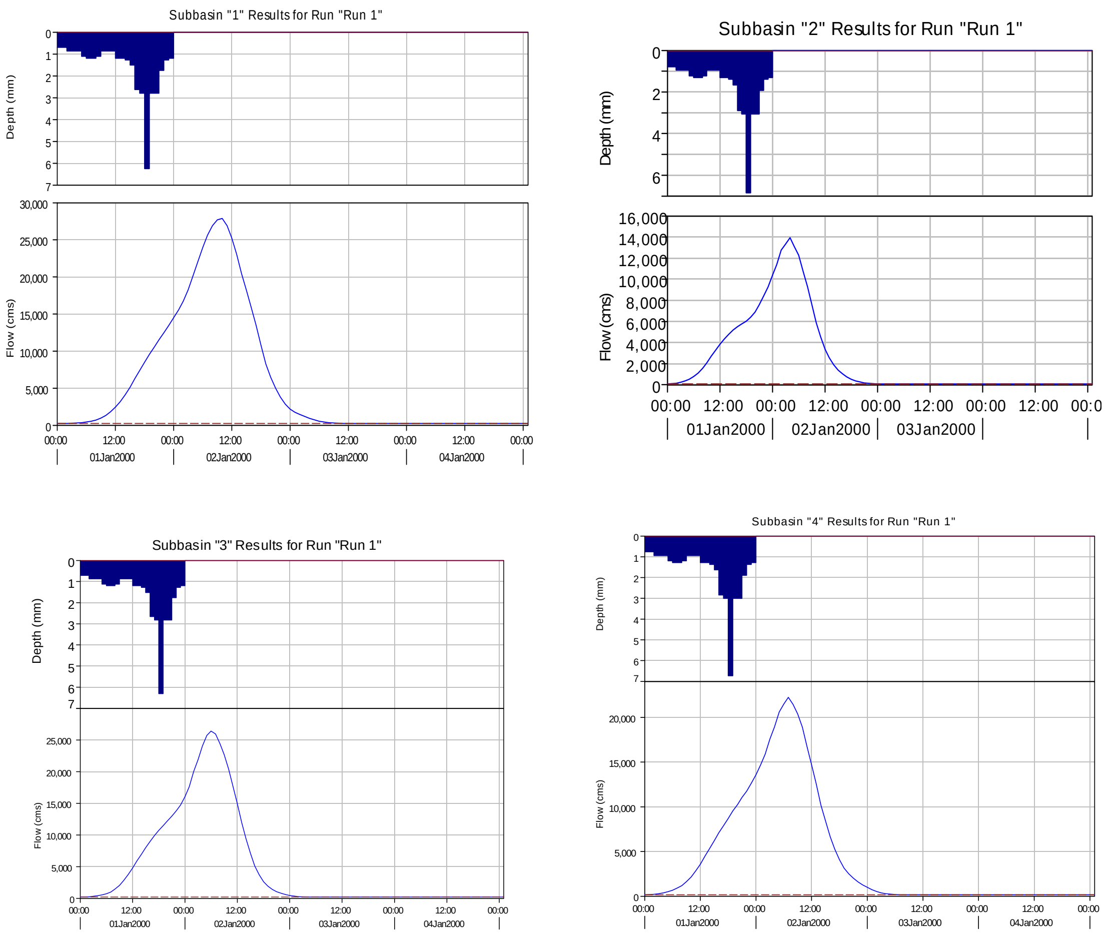

Figure 5: Design flood hydrographs for the four sub basins

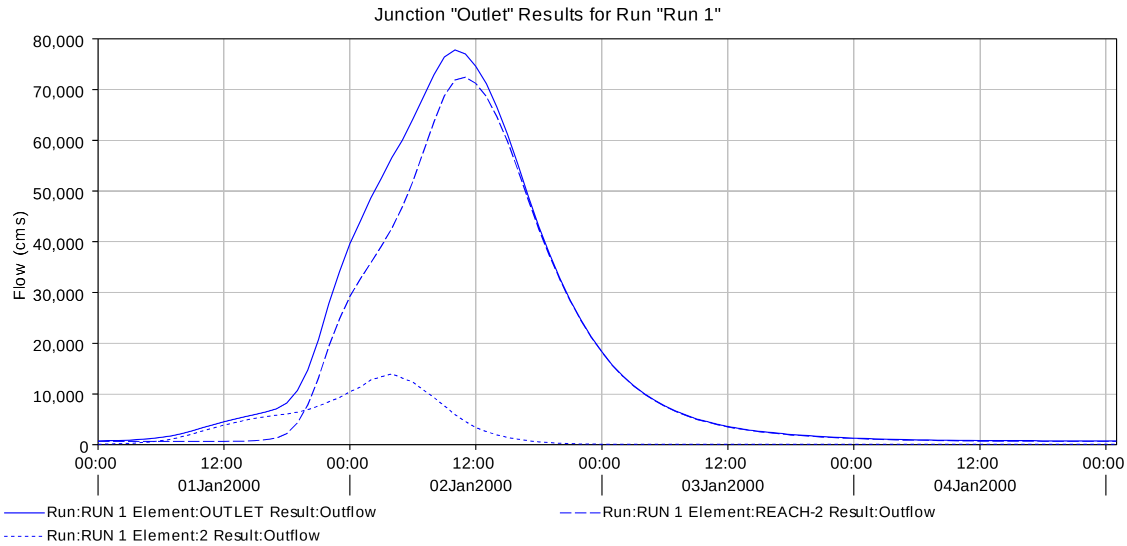

Figure 6: PMF Hydrograph at the outlet

V. CONCLUSIONS

Probable Maximum Precipitation (PMP) Atlas of various basins of India has been recently prepared jointly by Central Water Commission and India Meteorological Department, Government of India. This paper uses these grid wise PMPs given in the Atlas to estimate PMF hydrograph of at project site in Narmada River using HEC HMS model. The catchment area up the project site is divided into four sub catchments and unit hydrographs for each sub catchments are derived from the physiographic characteristics estimated using Arc GIS and Arc Hydro tools. A hydrologic model is setup in HEC-HMS for estimating flood hydrographs at outlet of each sub catchment and finally at the project site by hydrologic flood routing through the two reaches. The estimated 1day PMP are 40.20 cm, 43.91 cm, 40.57 cm and 43.23 cm for the catchments 1, 2, 3 and 4 respectively. The peak of probable maximum flood for the whole watershed at the outlet is estimated to be 77772.6 m^3/s.

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