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Estimation of Probable Maximum Precipitation (PMP) over the Hiramandalam Reservoir Catchment Using GIS

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Abstract: Reliable estimation of the Probable Maximum Precipitation (PMP) and the resulting Probable Maximum Flood (PMF) is essential for fixing the design flood of high-hazard hydraulic structures such as spillways and flood-control dams. This paper presents a GIS-based estimation of one-day PMP and the corresponding PMF for the catchment of the Hiramandalam Reservoir, located in Hiramandalam mandal of Srikakulam district, Andhra Pradesh. The catchment, delineated from SRTM DEM data using GIS tools, has an area of 85.922 sq.km, a longest flow path of 17.650 km, a centroidal flow path of 8.503 km and a catchment slope of 3.563 m/km. A Synthetic Unit Hydrograph (SUH) for the catchment was derived using the generalised relationships given by the Central Water Commission (CWC) for the East Coast Sub-zone 4(a), yielding a peak discharge of 196.63 cumecs at a time to peak of 2.5 hours and a time base of 14 hours. The catchment was overlaid on the isohyetal maps of the CWC PMP Atlas for the Mahanadi and Adjoining River Basins to identify the critical rainstorm (14 October 1931, centred at Pottangi, peak rainfall 546 mm). Using the storm transposition and maximisation approach, with Transposition and Maximisation Adjustment Factors extracted from the surrounding grid points, the one-day Standard Project Storm value was computed as 542.5 mm, which, after clock-hour correction, yielded a design one-day PMP of 592.5 mm. This depth was distributed into two 12-hour bells using CWC time-distribution coefficients, reduced by the design loss rate to obtain effective rainfall, arranged in the critical B2-B1 sequence, and convolved with the SUH ordinates to obtain the flood hydrograph. The resulting Probable Maximum Flood for the Hiramandalam Reservoir catchment was found to be 44,109.78 cumecs. The study illustrates how a GIS-integrated workflow can make PMP/PMF estimation reproducible and readily transferable to other small to medium ungauged catchments for spillway adequacy and dam-safety assessment.

Keywords: Probable Maximum Precipitation; Probable Maximum Flood; GIS; Synthetic Unit Hydrograph; Storm Transposition; Hiramandalam Reservoir; CWC PMP Atlas.

I. INTRODUCTION

The Probable Maximum Precipitation (PMP) is the greatest depth of rainfall for a given duration that is physically possible over a catchment at a given time of year, and it forms the basis for computing the Probable Maximum Flood (PMF) used to fix spillway design floods for high-hazard dams. Unlike a return-period flood, which carries a defined probability of exceedance, the PMF is a deterministic, extreme-event estimate intended to represent a practical upper limit on flood magnitude, so that failure of the structure and the resulting downstream hazard can be avoided with a very high degree of confidence.

A series of dam- and reservoir-related flood incidents reported across Andhra Pradesh in recent years [14] has drawn attention to the need for a careful, independent check of spillway adequacy at existing reservoirs, many of which were designed decades ago using limited hydro-meteorological data. For small and medium catchments that are ungauged, or where flood records are too short for a frequency analysis, the PMP-PMF route recommended by the Central Water Commission (CWC) remains the standard means of arriving at a design flood.

This paper reports a GIS-based estimation of the one-day PMP and the associated PMF for the catchment draining into the Hiramandalam Reservoir in Srikakulam district, Andhra Pradesh. The storm transposition and maximisation procedure of the CWC PMP Atlas for the Mahanadi and Adjoining River Basins is combined with a Synthetic Unit Hydrograph (SUH) obtained from CWC's regional relationships for East Coast Sub-zone 4(a). Catchment delineation and all physiographic computations were performed on an SRTM Digital Elevation Model (DEM) within a GIS environment, keeping the procedure transparent and repeatable for similar ungauged catchments.

II. OBJECTIVES OF THE STUDY

The present study is directed at the following specific objectives:

1) To delineate the catchment of the Hiramandalam Reservoir and compute its physiographic parameters from SRTM DEM data using GIS tools.
2) To derive a Synthetic Unit Hydrograph for the catchment using the generalised regional relationships prescribed by CWC for East Coast Sub-zone 4(a).
3) To identify the critical historical storm affecting the catchment from the CWC PMP Atlas for the Mahanadi and Adjoining River Basins and to estimate the one-day PMP by the storm transposition and maximisation method.
4) To distribute the estimated PMP over time using CWC's time-distribution coefficients and to compute the corresponding effective rainfall after deducting design losses.
5) To compute the Probable Maximum Flood for the catchment by convolving the effective rainfall with the Synthetic Unit Hydrograph, and to examine its implications for the reservoir's spillway design.

III. LITERATURE REVIEW

Several approaches to PMP estimation have been developed and applied to Indian and international river basins. Hershfield [4], [5] proposed a statistical method based on frequency analysis of annual maximum rainfall series, using an envelope frequency factor derived from a large number of raingauge stations; the method remains widely used because of its comparatively modest data requirements.

Koutsoyiannis [7] later examined the statistical basis of Hershfield's method and noted that its frequency factor cannot be interpreted as corresponding to a fixed, universal return period, which has encouraged more cautious use of the method in regional studies.

The storm-based moisture maximisation approach, in which an observed storm is scaled up to the highest atmospheric moisture likely to occur at the site, has been applied extensively to Indian river basins. Rakhecha et al. [8] estimated 2-day PMP for the Indian Peninsula using this approach, while Chavan and Srinivas [6] compared moisture-maximisation and Hershfield estimates for catchments in the Mahanadi river basin and reported considerable differences between the two methods. Foufoula-Georgiou [11] introduced a probabilistic storm-transposition framework for estimating the exceedance probability of extreme rainfall depths, and Rezacova et al. [12] applied storm maximisation and transposition to estimate PMP for river basins in the Czech Republic. Douglas and Barros [9] explored a multifractal approach to PMP estimation for the eastern United States, while Papalexiou and Koutsoyiannis [10] proposed reinterpreting PMP as an extreme rainfall quantile within a probabilistic framework rather than as a fixed physical limit.

In India, the Central Water Commission has adopted a hybrid storm-transposition and maximisation procedure, codified in the PMP Atlas series for different river basins [2], which combines historical storm identification, isohyetal analysis and grid-based transposition and maximisation adjustment factors.

This procedure, together with CWC's generalised Synthetic Unit Hydrograph relationships for different hydro-meteorological sub-zones [3], forms the basis of the PMP-to-PMF conversion adopted in most Indian dam-safety studies, including the present study for the Hiramandalam Reservoir catchment.

IV. STUDY AREA

The Hiramandalam Reservoir lies in Hiramandalam mandal of Srikakulam district, in the northern coastal belt of Andhra Pradesh, close to the state's border with Odisha (Fig. 1). It has a gross storage capacity of about 10 MCM. Its contributing catchment, delineated from SRTM DEM data, drains an area of 85.922 sq.km to a single outlet through one main stream. The catchment falls within East Coast Sub-zone 4(a) of the CWC's flood-estimation classification and is covered by the PMP Atlas for the Mahanadi and Adjoining River Basins. Rainfall in the region is governed by the south-west and north-east monsoons and, owing to the catchment's proximity to the Bay of Bengal, occasional depressions and cyclonic storms can produce intense short-duration rainfall, which is the principal reason a conservative, PMP-based design flood is warranted for the reservoir's spillway.

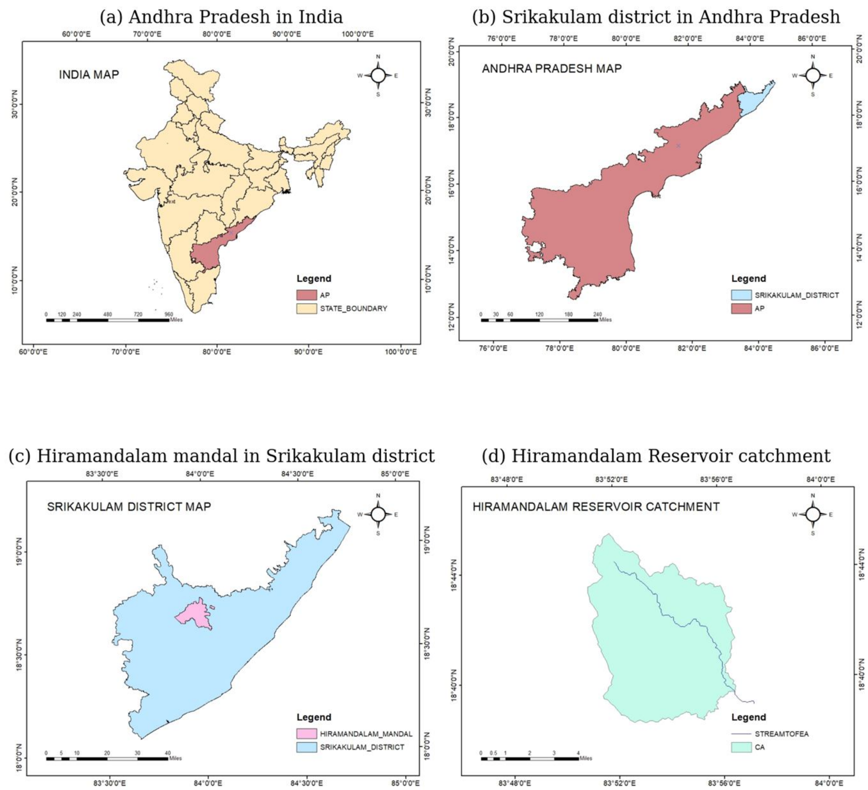

Fig. 1 Study area: (a) Andhra Pradesh in India; (b) Srikakulam district in Andhra Pradesh; (c) Hiramandalam mandal in Srikakulam district; (d) Hiramandalam Reservoir catchment delineated from SRTM DEM

V. DATA COLLECTION

The data and sources used for delineating the catchment and estimating the PMP and PMF are summarised in Table I.

Data / Parameter	Source / Method	Value
Digital Elevation Model	SRTM DEM, Bhuvan geoportal (ISRO)	Watershed and stream delineation
Catchment boundary & stream network	GIS delineation from DEM	Area = 85.922 sq.km
Contours / equivalent slope	Generated from DEM in GIS	S = 3.563 m/km
Physiographic parameters (L, Lc)	Measured in GIS from delineated layers	Table II
Critical 1-day storm rainfall	CWC PMP Atlas - Mahanadi & Adjoining Basins (Vol. I & II); isohyetal overlay, storm of 14 Oct 1931, Pottangi	Weighted Rainfall = 500 mm
Transposition & Maximisation factors (TAF, MAF)	CWC PMP Atlas grid-point data (Vol. I)	Average TAF=1.09, MAF=1.33
24-hr time-distribution coefficients	CWC PMP Atlas / sub-zone document	1st bell 76.80%, 2nd 23.20%
Design loss rate	Sub-zone hydro-meteorological document	0.75 cm/hr (first 9 hr)
SUH relationships	CWC generalised relations, East Coast Sub-zone 4(a)	Qp=196.63 m3/s, TB=14 hr

TABLE I Data Collected for PMP/PMF Estimation

The SRTM DEM of the study area, downloaded from the Bhuvan geoportal and used as the base layer for all subsequent GIS processing, is shown in Fig. 2.

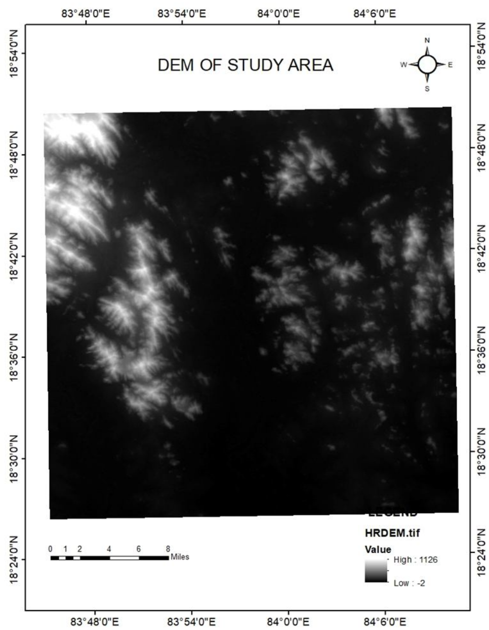

Fig. 2 SRTM DEM of the study area

VI. METHODOLOGY

The overall methodology followed for estimation of the PMP and PMF of the Hiramandalam Reservoir catchment is summarised in the flow chart at Fig. 3, and comprises four broad stages: (i) acquisition of DEM data and GIS-based delineation of the catchment and its physiographic parameters; (ii) derivation of a Synthetic Unit Hydrograph for the catchment; (iii) identification of the critical storm and estimation of the design PMP by storm transposition and maximisation; and (iv) critical arrangement of the design rainfall and its convolution with the SUH to obtain the design flood (PMF).

A. Physiographic Parameters and Synthetic Unit Hydrograph

The watershed and stream-reach layers derived from the DEM were used to measure the catchment area (A), the longest flow path (L) and the centroidal flow path (Lc). The catchment slope (S) was obtained from contours generated at a suitable interval, using the standard relation $S = \Sigma L_i(D_{i-1}+D_i)/L^2$, where Li is the length between successive contours and Di is the height above datum. The resulting physiographic parameters are given in Table II.

Physiographic Parameter	Symbol	Value	Unit
Catchment Area	A	85.922	km²
Longest Flow Path	L	17.650	km
Centroidal Flow Path	Lc	8.503	km
Catchment Slope	S	3.563	m/km

TABLE II Physiographic Parameters of Hiramandalam Reservoir Catchment

These parameters were used to derive a Synthetic Unit Hydrograph (SUH) for the catchment from the generalised regional relationships prescribed by CWC for East Coast Sub-zone 4(a). The resulting SUH parameters are listed in Table III, and the unit hydrograph for a unit (1 cm) effective rainfall is plotted in Fig. 4.

Parameter	Value	Unit
Time to peak, tp	2.5	hr
Peak discharge/area, qp	2.29	cumecs/km²
Time base, TB	14	hr
Width at 50% peak, W50	5.36	hr
Width at 75% peak, W75	3.01	hr
Rising width at 50%, WR50	1.93	hr
Rising width at 75%, WR75	1.20	hr
Time of peak, Tm	3.00	hr
Peak discharge, Qp	196.63	cumecs

TABLE III Synthetic Unit Hydrograph Parameters

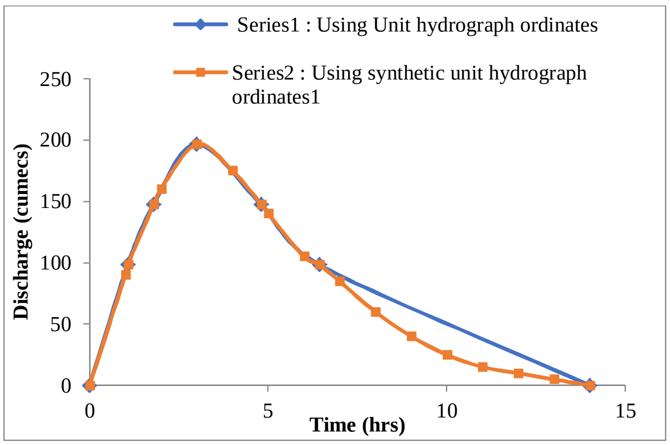

Fig. 4 1 cm Synthetic Unit Hydrograph of the Hiramandalam catchment

B. *Delineation of Catchment Area in ArcGIS*

Catchment delineation was carried out in ArcGIS following the standard DEM-based hydrological workflow shown in Fig. 3, comprising DEM acquisition from the Bhuvan (SRTM) portal, filling of spurious sinks in the DEM, computation of flow direction and flow accumulation grids, extraction of the stream network and stream order, and delineation of the watershed and catchment boundary. The successive outputs of this workflow for the Hiramandalam Reservoir catchment are shown in Fig. 5.

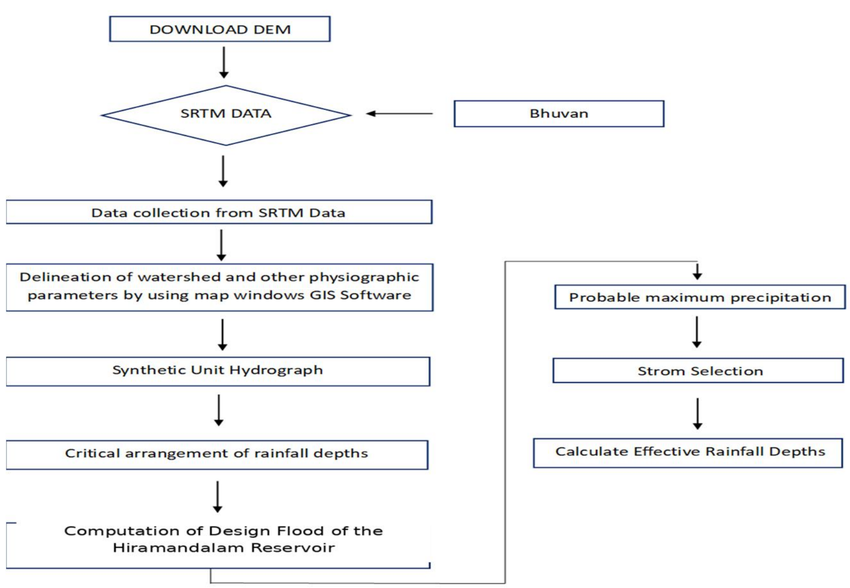

Fig. 3 Flow chart of the methodology adopted for PMP and PMF estimation

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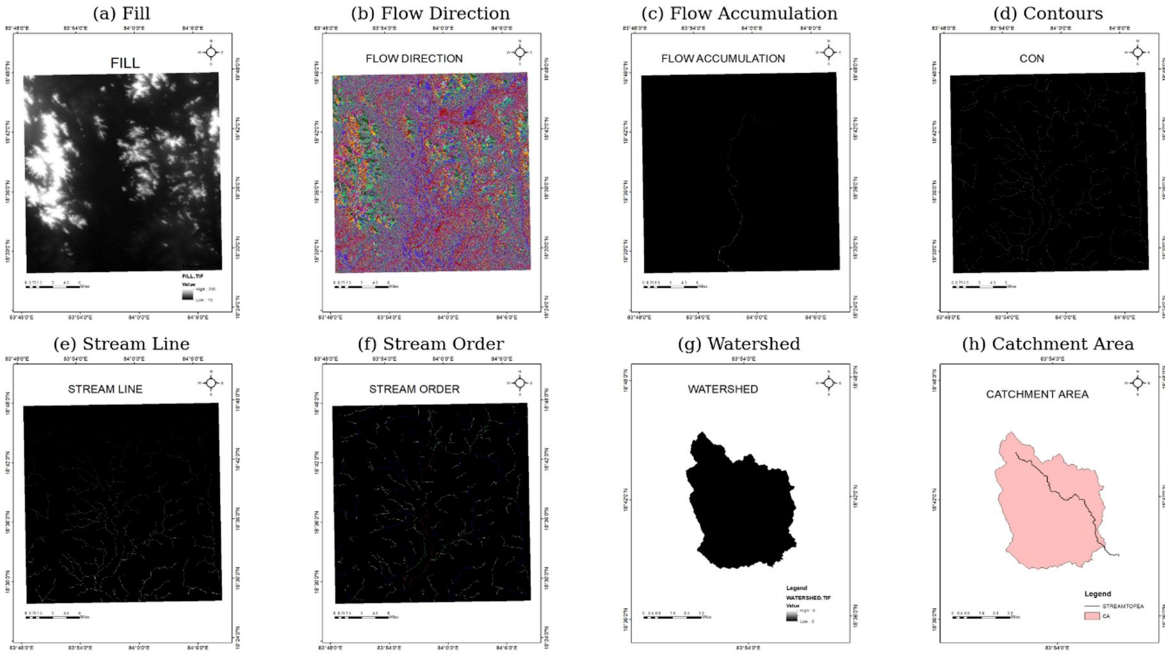

Fig. 5 Steps in catchment delineation using ArcGIS: (a) Fill; (b) Flow Direction; (c) Flow Accumulation; (d) Contours; (e) Stream Line; (f) Stream Order; (g) Watershed; (h) Catchment Area

C. Estimation of One-Day PMP

The catchment shapefile was overlaid on the 1-day storm isohyetal maps of the CWC PMP Atlas for the Mahanadi and Adjoining River Basins to identify the storm producing the most critical rainfall over the catchment. The storm of 14 October 1931, centred at Pottangi with a recorded peak 1-day rainfall of 546 mm, was found to be critical for the catchment. Digitising and intersecting the corresponding isohyetal map (PMP Atlas, Vol. II) with the catchment boundary showed the 500 mm isohyet covering the entire catchment, giving an area-weighted (100% area, 85.922 sq.km) mean rainfall of 500 mm.

Two CWC grid points surrounding the catchment were used to obtain the Transposition Adjustment Factor (TAF) and Maximisation Adjustment Factor (MAF), summarised in Table IV. The Standard Project Storm (SPP) depth was obtained by multiplying the area-weighted rainfall by the average TAF of these grid points.

Grid point (Geo-coordinates)	Serialised code	TAF	MAF
18, 83	MND318-01	1.21	1.23
19, 84	MND318-02	0.96	1.43
Average value	-	1.09	1.33

TABLE IV TAF and MAF at Surrounding Grid Points

SPP value = Weighted rainfall × Average TAF = 500 × 1.085 = 542.5 mm. Since this is a one-day estimate for a catchment well below 5000 sq.km, a clock-hour correction was applied: SPP × 1.15 = 623.875 mm, and SPP + 50 mm = 592.50 mm; the lower of the two, 592.50 mm, was adopted as the design one-day PMP for the Hiramandalam Reservoir catchment.

D. Rainfall Distribution and Effective Rainfall

The 592.50 mm one-day PMP was distributed into two successive 12-hour bells using CWC's time-distribution coefficients for the region, normalised to the 24-hour total: the first bell was found to carry 76.80% of the depth (455.04 mm) and the second bell the remaining 23.20% (137.46 mm).

Applying the normalised hourly coefficients to each bell gave the cumulative and incremental rainfall at each hour; a design loss rate of 0.75 cm/hr, taken from the sub-zone hydro-meteorological document, was then deducted for the first nine hours of each bell (reducing to nil thereafter) to obtain the effective-rainfall hyetograph. Table V summarises this computation for the first 12-hour bell; the second bell follows the same procedure.

Time (hr)	Distribution Coefficient (%)	Incremental Rainfall 1st Bell (cm)	Incremental Rainfall 2nd Bell(cm)	Design Loss Rate (cm/hr)	Effective Incremental Rainfall 1st Bell (cm)	Effective Incremental Rainfall 2nd Bell (cm)
1	23	9.17	2.77	0.75	8.42	2.02
2	38	5.21	1.57	0.75	4.46	0.82
3	48	5.21	1.57	0.75	4.46	0.82
4	57	3.29	1.00	0.75	2.54	0.25
5	65	3.29	1.00	0.75	2.54	0.25
6	110	3.29	1.00	0.75	2.54	0.25
7	77	3.12	0.94	0.75	2.37	0.19
8	82	3.12	0.94	0.75	2.37	0.19
9	88	3.12	0.94	0.75	2.37	0.19
10	92	2.23	0.67	0.00	2.23	0.67
11	96	2.23	0.67	0.00	2.23	0.67
12	100	2.23	0.67	0.00	2.23	0.67

TABLE V Hourly Time-Distribution and Effective Rainfall (First 12-Hour Bell; Second Bell Analogous)

E. Critical Sequencing and Computation of PMF

Following Section 9.6.1 of the Flood Estimation Report methodology, the two 12-hour effective-rainfall bells were arranged in the critical B2-B1 sequence, i.e. with the larger bell preceded by the smaller bell, so as to produce the maximum possible flood peak. The resulting critically-sequenced effective-rainfall hyetograph was convolved with the SUH ordinates to obtain the direct surface runoff hydrograph, to which a constant base flow of 0.052 cumecs was added to obtain the final flood hydrograph. The peak of this hydrograph is the Probable Maximum Flood (PMF) for the catchment.

VII. RESULTS AND DISCUSSION

The computed one-day PMP for the Hiramandalam Reservoir catchment is 592.50 mm, obtained by transposing and maximising the critical storm of 14 October 1931 (Pottangi) using CWC PMP Atlas grid data. Convolving the SUH with the critically-sequenced effective rainfall (Fig. 6) gives a flood hydrograph that rises from a base flow of about 0.05 cumecs to a peak of 44,109.78 cumecs (about 1,557,736.98 cusecs) at the 35th hour, and recedes to near-zero by about the 55th hour. Table VI lists selected ordinates of the computed hydrograph.

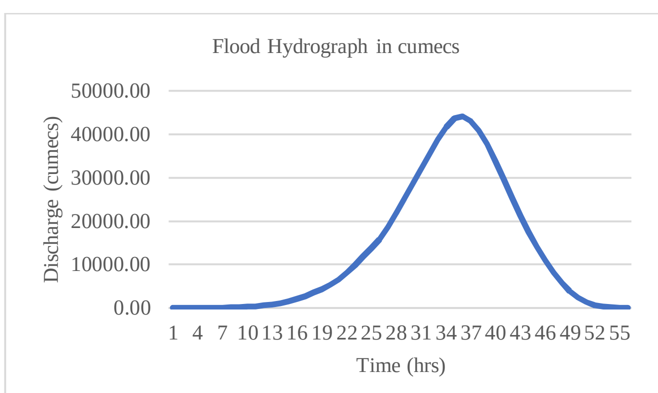

Fig. 6 Probable Maximum Flood (PMF) hydrograph for the Hiramandalam Reservoir catchment

Time (hrs)	Flood Discharge (cumecs)	Time (hrs)	Flood Discharge (cumecs)
0	0.05	35 (Peak)	44,109.78
5	28.35	36	43,024.07
10	369.87	40	29,592.25
15	2,008.56	45	10,959.05
20	6,493.66	50	1,334.25
25	15,865.01	55	0.05
30	32,033.61	-	-

TABLE VI Selected Ordinates of the PMF Hydrograph

The estimated PMF of about 44,110 cumecs is very large in relation to the reservoir's gross storage of 10 MCM and its modest catchment area of 85.922 sq.km. This is characteristic of PMP/PMF-based design: since the PMP represents an extreme, physically-limiting storm rather than a statistically frequent event, the resulting PMF is intentionally conservative and is meant to bound spillway capacity requirements rather than to represent an expected flood. The scale of the estimate obtained here reinforces the case for verifying the adequacy of the existing spillway of the Hiramandalam Reservoir, particularly given recent dam-related flood incidents reported elsewhere in Andhra Pradesh [14].

The complete workflow — DEM acquisition, watershed and stream delineation, computation of physiographic parameters, derivation of the SUH, isohyetal overlay for storm identification, TAF/MAF extraction, clock-hour correction, rainfall distribution and convolution — was implemented using GIS tools throughout, so that the same procedure can be applied to other ungauged catchments within the same CWC sub-zone with minimal modification.

VIII. CONCLUSION

A GIS-based procedure was used to estimate the one-day PMP and the corresponding PMF for the catchment of the Hiramandalam Reservoir in Srikakulam district, Andhra Pradesh. The study leads to the following conclusions:

1) The Hiramandalam Reservoir catchment, delineated from SRTM DEM data, has an area of 85.922 sq.km, a longest flow path of 17.650 km, a centroidal flow path of 8.503 km and a catchment slope of 3.563 m/km.
2) The Synthetic Unit Hydrograph derived from CWC's generalised relationships for East Coast Sub-zone 4(a) has a peak discharge of 196.63 cumecs at a time to peak of 2.5 hours and a time base of 14 hours.
3) Overlay of the catchment on the CWC PMP Atlas for the Mahanadi and Adjoining River Basins identified the storm of 14 October 1931 at Pottangi as critical; storm transposition and maximisation using grid-based TAF and MAF values gave a design one-day PMP of 592.50 mm after clock-hour correction.
4) Distribution of the PMP into two 12-hour bells, reduction by the design loss rate, critical B2-B1 sequencing and convolution with the SUH together gave a Probable Maximum Flood of 44,109.78 cumecs for the catchment.
5) The magnitude of the estimated PMF underlines the importance of re-checking existing and proposed spillway capacities at the Hiramandalam Reservoir, and demonstrates a GIS-integrated workflow that can be extended to other ungauged catchments within the same sub-zone.

IX. ACKNOWLEDGMENT

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