



ESTIMATION OF PROBABLE MAXIMUM FLOOD FOR THE PAIDIPALEM RESERVOIR CATCHMENT

A GIS-Based Storm Transposition and Synthetic Unit Hydrograph Approach

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Abstract : Reliable estimation of the Probable Maximum Flood (PMF) is essential for verifying the flood-handling capacity of high-hazard hydraulic structures such as spillways and flood-control dams. This paper presents a GIS-based estimation of the one-day design storm (PMP) and the corresponding PMF for the catchment of the Paidipalem Reservoir, a balancing reservoir of the Gandikota Lift Irrigation Scheme located in Simhadripuram mandal of YSR Kadapa district, Andhra Pradesh. The catchment, delineated from SRTM DEM data using ArcGIS, has an area of 12.141 sq.km, a longest flow path of 6.537 km, a centroidal flow path of 4.357 km and a catchment slope of 7.087 m/km. A Synthetic Unit Hydrograph (SUH) derived from the Central Water Commission (CWC) regional relationships for Krishna and Pennar Sub-zone 3(h) gave a peak discharge of 9.89 cumecs, a time to peak of 1.5 hours and a time base of 10 hours. The storm of 6 October 1994 centred at Atmakur (464 mm) was transposed to the catchment, giving an area-weighted rainfall of 400 mm and, with the grid-point Transposition Adjustment Factor, a Standard Project Storm depth of 389.0 mm, which after clock-hour correction yielded a design one-day PMP of 439.0 mm. This depth was distributed into two 12-hour bells (69.20% and 30.80%), reduced by a design loss rate of 0.10 cm/hr, arranged in the critical B2-B1 sequence and convolved with the SUH ordinates. After adding a base flow of 0.61 cumecs, the PMF was found to be 123.09 cumecs (4,346.99 cusecs) at the 21st hour, which is lower than the original design flood of 169.9 cumecs. The workflow is reproducible and can be transferred to other ungauged catchments of the same sub-zone.

IndexTerms - Probable Maximum Precipitation, Probable Maximum Flood, GIS, ArcGIS, Synthetic Unit Hydrograph, Storm Transposition, Paidipalem Reservoir.

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 [1], and it forms the basis for computing the Probable Maximum Flood (PMF) used to fix the design flood of 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.

Dam- and reservoir-related flood incidents reported in Andhra Pradesh in recent years [2] have drawn attention to the need for a careful, independent check of the flood-handling capacity of existing reservoirs, many of which were planned decades ago with 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 [3], [4].

This paper reports a GIS-based estimation of the one-day PMP and the associated PMF for the catchment draining into the Paidipalem Reservoir in Simhadripuram mandal of YSR Kadapa district, Andhra Pradesh. The storm transposition procedure of the CWC PMP Atlas is combined with a Synthetic Unit Hydrograph (SUH) obtained from CWC's regional relationships for Krishna and Pennar Sub-zone 3(h). Catchment delineation and all physiographic computations were performed on an SRTM Digital Elevation Model (DEM) using ArcGIS, 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 Paidipalem Reservoir and compute its physiographic parameters from SRTM DEM data using ArcGIS.
- 2) To derive a Synthetic Unit Hydrograph for the catchment using the generalised regional relationships prescribed by CWC for Krishna and Pennar Sub-zone 3(h).

- 3) To identify the critical historical storm near the catchment from the CWC PMP Atlas for the Cauvery and East Flowing River Basins and to estimate the one-day PMP by the storm transposition method.
- 4) To distribute the estimated PMP over time using CWC's time-distribution coefficients and to compute the corresponding effective rainfall after deducting the design loss.
- 5) To compute the Probable Maximum Flood by convolving the effective rainfall with the Synthetic Unit Hydrograph, and to compare it with the original design flood of the reservoir.

III. LITERATURE REVIEW

Several approaches to PMP estimation have been developed and applied to Indian and international river basins. Hershfield [5], [6] 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 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 [9] compared moisture-maximisation and Hershfield estimates for catchments in the Mahanadi river basin and reported considerable differences between the two methods. Foufoula-Georgiou [10] introduced a probabilistic storm-transposition framework for estimating the exceedance probability of extreme rainfall depths, and Rezacova et al. [11] applied storm maximisation and transposition to river basins in the Czech Republic. Douglas and Barros [12] explored a multifractal approach for the eastern United States, while Papalexiou and Koutsoyiannis [13] proposed reinterpreting PMP as an extreme rainfall quantile within a probabilistic framework rather than as a fixed physical limit.

In India, the CWC has adopted a storm-transposition procedure, codified in the PMP Atlas series for different river basins [3], which combines historical storm identification, isohyetal analysis and grid-based transposition adjustment factors. Together with CWC's generalised SUH relationships for different hydro-meteorological sub-zones [4], it forms the basis of the PMP-to-PMF conversion adopted in most Indian dam-safety studies, including the present one.

On the GIS side, ArcGIS provides a Hydrology toolset within its Spatial Analyst extension for terrain processing and watershed delineation [14]. Raster DEMs are generally favoured for terrain processing because their matrix structure suits computer processing better than triangulated irregular networks [15], and the D8 flow-direction method implemented in these tools derives flow directions and upslope contributing areas from such grids [16]. This combination allows catchment delineation directly from freely available SRTM data.

IV. STUDY AREA

The Paidipalem Reservoir is located in Simhadripuram mandal of YSR Kadapa district in the Rayalaseema region of Andhra Pradesh (Fig. 1), at latitude 14°39' N and longitude 78°10' E. It serves as a balancing reservoir within the Gandikota Lift Irrigation Scheme (GKLI), receiving water lifted from the Gandikota Reservoir on the Pennar River. The reservoir has a gross storage capacity of 169.9 MCM (6.00 TMC) and is intended to provide irrigation facilities to an extent of 47,500 acres in the Rabi season, using lifted water during the dry season when natural rainfall is insufficient. Its spillway was designed for a peak discharge of about 168 m³/s.

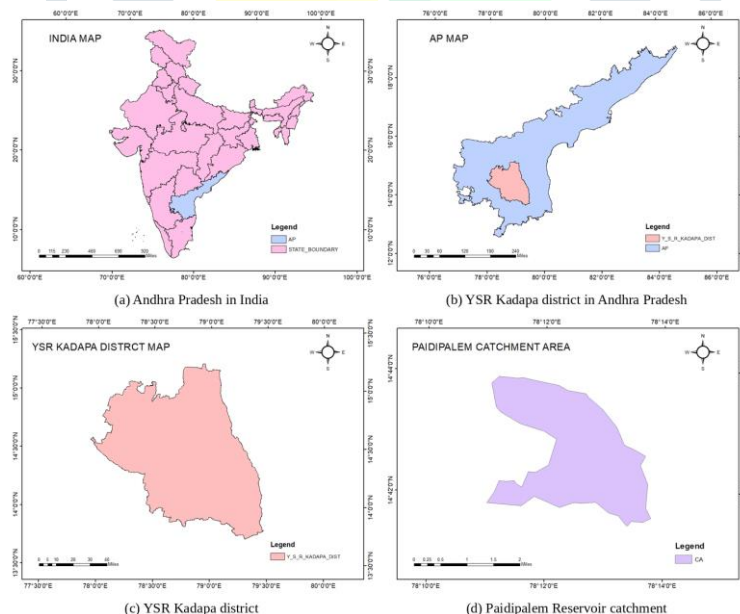


Fig. 1 Study area: (a) Andhra Pradesh in India; (b) YSR Kadapa district in Andhra Pradesh; (c) YSR Kadapa district; (d) Paidipalem Reservoir catchment

The contributing catchment, delineated from SRTM DEM data, drains an area of 12.141 sq.km to a single outlet through one main stream (Fig. 4) and is mainly rain-fed and cultivated land. The average annual rainfall of the catchment is 644 mm, received mainly during the south-west and north-east monsoons. The catchment lies within Krishna and Pennar Sub-zone 3(h) of the CWC flood-estimation classification, and the CWC PMP Atlas for the Cauvery and East Flowing River Basins covers the area.

V. DATA COLLECTION

The data and sources used for delineating the catchment and estimating the PMP and PMF are summarised in Table 1. The SRTM DEM was downloaded from the CGIAR-CSI SRTM portal [17] and used as the base layer for all GIS processing, and the outlet point was located at the reservoir site with the help of Google Earth Pro. The DEM of the study area is shown in Fig. 2.

Table 1 Data collected for PMP/PMF estimation

Data / Parameter	Source / Method	Value
Digital Elevation Model	SRTM DEM, CGIAR-CSI portal [17]	Watershed and stream delineation
Catchment boundary and stream network	GIS delineation from DEM (ArcGIS)	Area = 12.141 sq.km
Equivalent slope	Contours generated from DEM	$S = 7.087 \text{ m/km}$
Physiographic parameters (L, Lc)	Measured in GIS from delineated layers	Table 2
Critical 1-day storm rainfall	CWC PMP Atlas, Cauvery and East Flowing Basins [3]; storm of 6 Oct 1994, Atmakur (464 mm)	Weighted rainfall = 400 mm
Transposition and maximisation factors (TAF, MAF)	CWC PMP Atlas grid-point data [3]	Average TAF = 0.97, MAF = 1.36
24-hr time-distribution coefficients	CWC FER, Sub-zone 3(h) [4]	1st bell 69.20%, 2nd bell 30.80%
Design loss rate	CWC FER, Sub-zone 3(h) [4]	0.10 cm/hr (plain terrain)
Base flow	CWC FER, Sub-zone 3(h) [4]	0.05 cumecs/sq.km = 0.61 cumecs
SUH relationships	CWC generalised relations, Sub-zone 3(h) [4]	$Q_p = 9.89 \text{ cumecs}$, TB = 10 hr

In accordance with the CWC manual on estimation of design flood [18], dams are classified by gross storage and hydraulic head, and the inflow design flood for a large dam (gross storage greater than 60 Mm^3) is the PMF, whereas intermediate and small dams are designed for the Standard Project Flood and the 100-year flood respectively. With a gross storage of 169.9 MCM, the Paidipalem Reservoir falls in the large category, and the PMF is therefore adopted as its design flood.

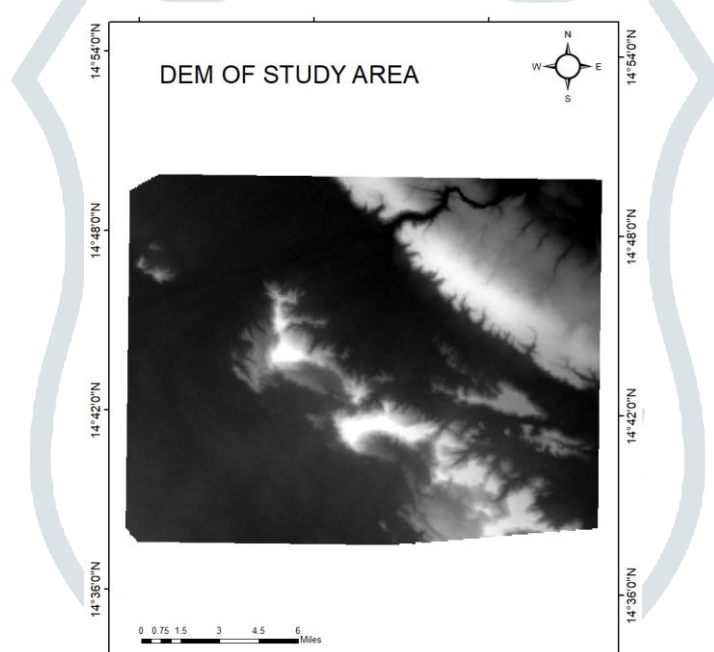


Fig. 2 SRTM DEM of the study area

VI. METHODOLOGY

The overall methodology followed for estimation of the PMP and PMF of the Paidipalem Reservoir catchment is summarised in the flow chart in 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 (iv) critical arrangement of the design rainfall and its convolution with the SUH to obtain the design flood (PMF).

A. Catchment Delineation in ArcGIS and Physiographic Parameters

Catchment delineation was carried out in ArcGIS using the Hydrology tools of the Spatial Analyst extension [14], following the standard DEM-based workflow shown in Fig. 3. Spurious sinks in the SRTM DEM were first removed (Fill), the flow direction was computed by the D8 method [16], and the flow accumulation grid was derived from it. The stream network was extracted from the flow accumulation grid by applying a threshold (Con), and the stream link, stream order and stream-to-feature (vector stream) layers were then generated. The outlet was placed on the stream at the reservoir site, from which the watershed was delineated and converted to the catchment polygon. The successive outputs, ending with the watershed and the catchment with its stream reach and outlet, are shown in Fig. 4.

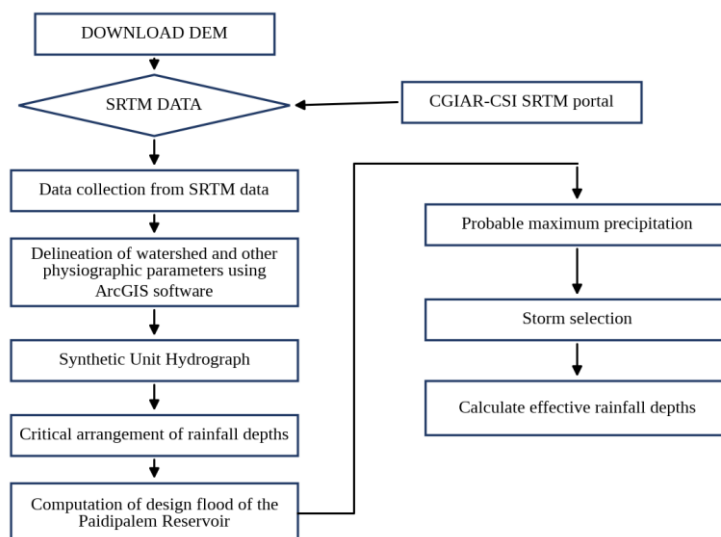


Fig. 3 Flow chart of the methodology adopted for PMP and PMF estimation

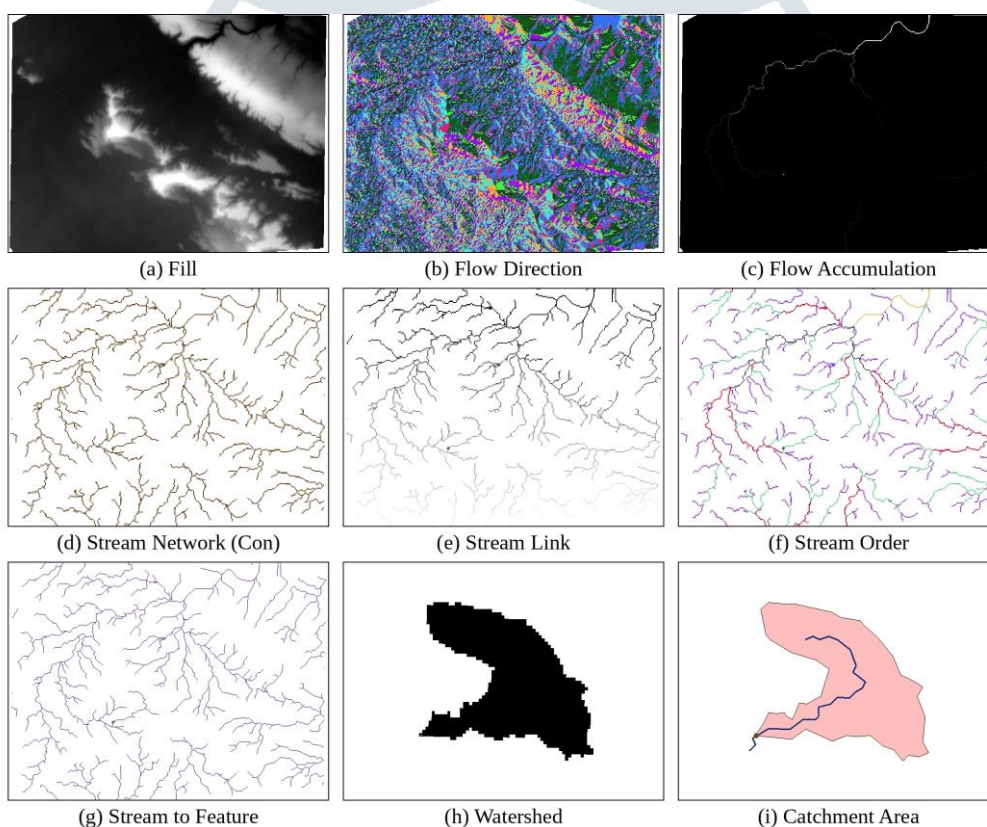


Fig. 4 Steps in catchment delineation: (a) Fill; (b) Flow Direction; (c) Flow Accumulation; (d) Stream Network (Con); (e) Stream Link; (f) Stream Order; (g) Stream to Feature; (h) Watershed; (i) Catchment Area

The watershed and stream-reach layers 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 from the DEM, using the equivalent-slope relation

$$S = \Sigma L_i(D_{i-1} + D_i) / L^2 \quad (1)$$

where L_i is the length of the stream between successive contours and D_i is the height above datum; here the main stream rises from RL 252 m at the outlet to RL 316 m at its upstream end. The resulting physiographic parameters are given in Table 2.

Table 2 Physiographic parameters of the Paidipalem Reservoir catchment

Physiographic Parameter	Symbol	Value	Unit
Catchment Area	A	12.141	km ²
Longest Flow Path	L	6.537	km
Centroidal Flow Path	Lc	4.357	km
Catchment Slope	S	7.087	m/km

B. Synthetic Unit Hydrograph

Since observed rainfall-runoff data are not available for the catchment, the SUH parameters were computed from the equations recommended in the CWC Flood Estimation Report for Krishna and Pennar Sub-zone 3(h) [4] using A, L, Lc and S. The resulting parameters are listed in Table 3, and the unit hydrograph for 1 cm effective rainfall is plotted in Fig. 5. The ordinates were read from the smoothed curve at hourly intervals (0, 4.50, 9.89, 7.50, 4.94, 3.00, 1.50, 0.75, 0.25, 0.01 and 0 cumecs for hours 0 to 10). Their sum of 32.34 cumecs gives a direct-runoff check depth of $32.34 \times 0.36 / 12.141 = 0.96$ cm, which is acceptably close to 1 cm.

Table 3 Synthetic Unit Hydrograph parameters

Parameter	Computed	Adopted	Unit
Time to peak, t_p	0.98	1.50	hr
Peak discharge per unit area, q_p	0.81	0.81	cumecs/km ²
Time base, TB	9.14	10.00	hr
Width at 50% peak, W50	2.97	2.97	hr
Width at 75% peak, W75	1.76	1.76	hr
Rising width at 50% peak, WR50	0.97	0.97	hr
Rising width at 75% peak, WR75	0.70	0.70	hr
Time of peak, T_m	2.00	2.00	hr
Peak discharge, Q_p	9.89	9.89	cumecs

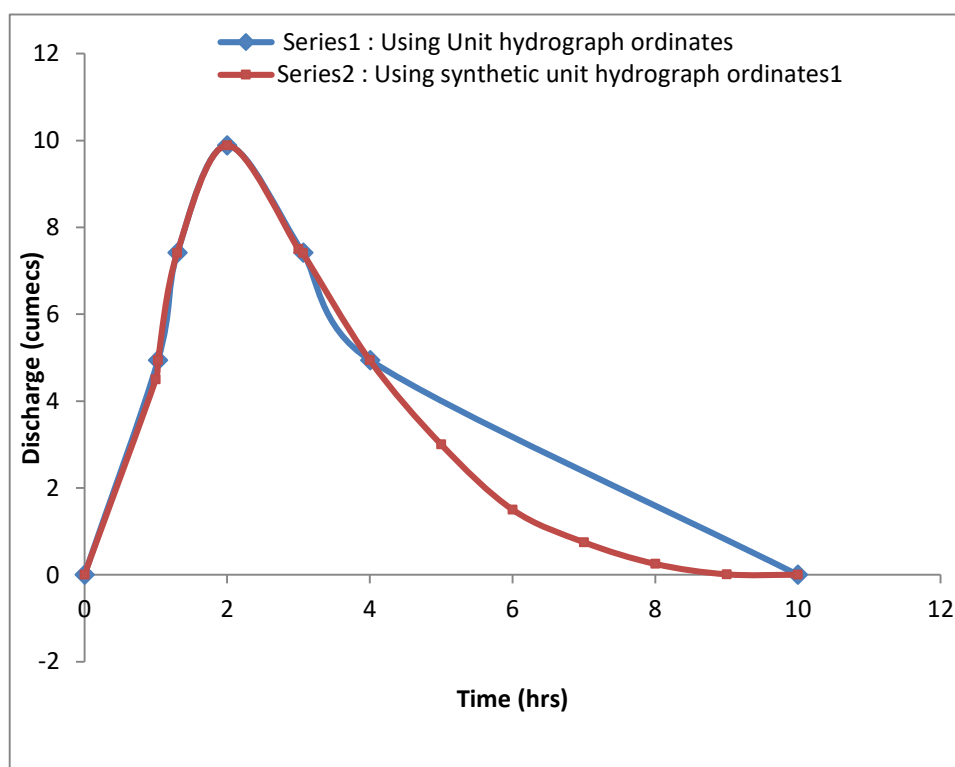


Fig. 5 1 cm Synthetic Unit Hydrograph of the Paidipalem Reservoir catchment

C. Estimation of One-Day PMP

As the time base of the SUH (10 hr) is less than 24 hr, a one-day storm is adopted. The CWC PMP Atlas for the Cauvery and East Flowing River Basins [3] places the Atmakur storm centre close to the catchment, with a peak 1-day rainfall of 464 mm on 6 October 1994. The catchment was overlaid on the isohyetal map of this storm in the Atlas [3]; the 400 mm isohyet covers the entire catchment (100% of 12.141 sq.km, $\Sigma P \cdot A = 4856.4$), giving an area-weighted mean rainfall of 400 mm.

Four CWC grid points surrounding the catchment were used to obtain the Transposition Adjustment Factor (TAF), summarised with the Maximisation Adjustment Factor (MAF) in Table 4. The Standard Project Storm (SPP) depth was obtained by multiplying the area-weighted rainfall by the average TAF:

Table 4 TAF and MAF at surrounding grid points

S.No	Grid point (geo-coordinates)	Serialised code	TAF	MAF
1	14°, 79°	CAU304-01	1.00	1.36
2	14°, 78°	CAU30-02	0.91	1.36
3	15°, 79°	CAU304-04	1.02	1.36
4	15°, 78°	CAU304-05	0.96	1.36
	Average value	-	0.97	1.36

$$SPP = P_w \times TAF_{avg} = 400 \times 0.9725 = 389.0 \text{ mm} \quad (2)$$

On average, the maximum 24-hr rainfall is 1.15 times the corresponding daily rainfall, limited to an excess of 50 mm; this clock-hour correction converts the 1-day storm depth to the corresponding 24-hr depth:

$$P_{24} = \min (1.15 \times SPP, SPP + 50) = \min (447.35, 439.00) = 439.00 \text{ mm} \quad (3)$$

The lower value of 439.00 mm was adopted as the design one-day PMP for the Paidipalem Reservoir catchment.

D. Rainfall Distribution and Effective Rainfall

The 439.00 mm design depth was distributed into two successive 12-hour bells using CWC's hourly distribution coefficients for the sub-zone [4], normalised to the 12-hour bell: the first bell carries 69.20% of the depth (303.80 mm) and the second bell the remaining 30.80% (135.21 mm). The hourly coefficients were used to obtain the incremental rainfall at each hour, and a design loss rate of 0.10 cm/hr, recommended for plain terrain [4], was deducted to obtain the effective-rainfall hyetograph. Table 5 summarises this computation for both bells.

Table 5 Hourly time-distribution and effective rainfall for the two 12-hour bells

Time (hr)	Dist. coeff. (%)	Normalised coeff. (%)	Incremental rainfall, 1st bell (cm)	Incremental rainfall, 2nd bell (cm)	Design loss rate (cm/hr)	Effective rainfall, 1st bell (cm)	Effective rainfall, 2nd bell (cm)
1	15.60	23	6.12	2.73	0.10	6.02	2.63
2	25.40	37	3.48	1.55	0.10	3.38	1.45
3	33.00	48	3.48	1.55	0.10	3.38	1.45
4	39.30	57	2.20	0.98	0.10	2.10	0.88
5	44.50	64	2.20	0.98	0.10	2.10	0.88
6	49.60	72	2.20	0.98	0.10	2.10	0.88
7	53.00	77	2.08	0.93	0.10	1.98	0.83
8	56.30	81	2.08	0.93	0.10	1.98	0.83
9	59.60	86	2.08	0.93	0.10	1.98	0.83
10	62.80	91	1.49	0.66	0.10	1.39	0.56
11	66.00	95	1.49	0.66	0.10	1.39	0.56
12	69.20	100	1.49	0.66	0.10	1.39	0.56

E. Critical Sequencing and Computation of PMF

Following Section 9.6.1 of the CWC Flood Estimation Report [4], the effective rainfall was arranged so that the largest depth is preceded by the second largest and succeeded by the third largest, which gives the bell sequence B2-B1 (the smaller second bell preceding the larger first bell). The resulting critically sequenced effective-rainfall pulses (cm), taken in order, were 0.56, 0.83, 0.83, 0.83, 0.88, 0.88, 1.45, 1.45, 2.63, 0.88, 0.56, 1.39, 1.98, 1.98, 1.98, 2.10, 2.10, 3.38, 3.38, 6.02, 2.10 and 1.39. These pulses were convolved with the SUH ordinates to obtain the direct surface runoff hydrograph:

$$Q_t = \sum P_j U_{t-j+1} + Q_b \quad (4)$$

where Q_t is the flood discharge at hour t , P_j is the effective rainfall of the j -th pulse, U is the SUH ordinate and Q_b is the base flow. A constant base flow of 0.05 cumecs per sq.km, i.e. $0.05 \times 12.141 = 0.61$ cumecs, was added to obtain the final flood hydrograph, and its peak is the PMF of the catchment.

VII. RESULTS AND DISCUSSION

The computed design one-day PMP for the Paidipalem Reservoir catchment is 439.00 mm, obtained by transposing the storm of 6 October 1994 (Atmakur) with CWC grid-point data and applying the clock-hour correction. Convolving the SUH with the critically sequenced effective rainfall gives a flood hydrograph (Fig. 6) that rises from a base flow of 0.61 cumecs to a peak of 123.09 cumecs (4,346.99 cusecs) at the 21st hour, and recedes to the base flow by about the 31st hour. The corresponding peak specific discharge is about 10.1 cumecs per sq.km. Table 6 lists the ordinates of the computed hydrograph.

Table 6 Ordinates of the PMF hydrograph (direct runoff and flood hydrograph including base flow)

Time (hr)	Direct runoff (cumecs)	Flood discharge (cumecs)	Time (hr)	Direct runoff (cumecs)	Flood discharge (cumecs)
0	0.00	0.61	16	60.01	60.61
1	2.52	3.13	17	63.54	64.15
2	9.27	9.88	18	71.61	72.22
3	16.14	16.75	19	85.51	86.12
4	20.94	21.54	20	107.51	108.11
5	24.17	24.78	21	122.48	123.09
6	26.32	26.93	22	104.25	104.86
7	30.08	30.69	23	76.57	77.17
8	36.31	36.92	24	47.01	47.62
9	46.12	46.73	25	25.60	26.20
10	52.81	53.41	26	12.71	13.32
11	44.66	45.26	27	5.20	5.81
12	38.80	39.41	28	1.63	2.23
13	42.59	43.19	29	0.37	0.98
14	49.73	50.33	30	0.01	0.62
15	55.56	56.17	31	0.00	0.61

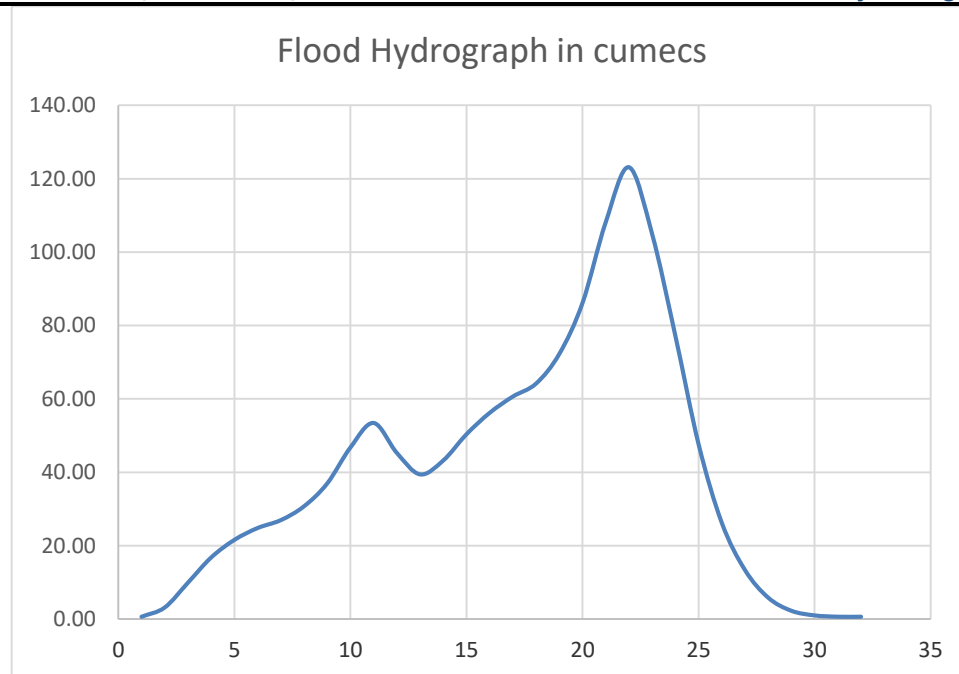


Fig. 6 Probable Maximum Flood (PMF) hydrograph for the Paidipalem Reservoir catchment

The estimated PMF of 123.09 cumecs (4,346.99 cusecs) is about 72% of the original design flood of 169.9 cumecs (5,997.5 cusecs), a difference of about 47 cumecs, and it is also below the spillway design discharge of about 168 m³/s. On this basis the existing spillway capacity appears adequate for the computed PMF inflow. It should be noted that the PMF is an inflow flood: the attenuation of the peak by reservoir storage has not been considered, which makes the estimate conservative, whereas the use of a 90 m SRTM DEM and of regional CWC relationships introduces uncertainty in the physiographic parameters and the SUH. A reservoir flood-routing study with the survey-based catchment parameters would therefore be the appropriate next step to confirm spillway adequacy.

The complete workflow, comprising DEM acquisition, watershed and stream delineation, computation of physiographic parameters, derivation of the SUH, storm identification and transposition, clock-hour correction, rainfall distribution and convolution, was implemented with ArcGIS and spreadsheet computation, 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 Paidipalem Reservoir in YSR Kadapa district, Andhra Pradesh. The study leads to the following conclusions:

- 1) The Paidipalem Reservoir catchment, delineated from SRTM DEM data using ArcGIS, has an area of 12.141 sq.km, a longest flow path of 6.537 km, a centroidal flow path of 4.357 km and a catchment slope of 7.087 m/km.
- 2) The Synthetic Unit Hydrograph derived from CWC's generalised relationships for Krishna and Pennar Sub-zone 3(h) has a peak discharge of 9.89 cumecs at a time to peak of 1.5 hours and a time base of 10 hours.
- 3) The storm of 6 October 1994 centred at Atmakur, transposed with grid-based TAF values and corrected for clock hours, gave a design one-day PMP of 439.00 mm.
- 4) Distribution of the PMP into two 12-hour bells, reduction by the design loss rate of 0.10 cm/hr, critical B2-B1 sequencing and convolution with the SUH, together with a base flow of 0.61 cumecs, gave a PMF of 123.09 cumecs (4,346.99 cusecs).
- 5) The estimated PMF is about 72% of the original design flood of 169.9 cumecs, indicating that the existing spillway capacity appears adequate; a reservoir routing study is recommended to confirm this, and the workflow can be extended to other ungauged catchments of the same sub-zone.

IX. ACKNOWLEDGMENT

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