



iJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** IX **Month of publication:** September 2026

DOI: <https://doi.org/10.22214/ijraset.2026.84959>

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Assessment of Rainfall-Runoff Dynamics and Reservoir Inflow Response under Rainfall Scenarios in the Yeleswaram Catchment Using HEC-HMS

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Abstract: A continuous daily rainfall–runoff model of the Yeleswaram catchment (2378.03 km²), which drains into the Yeleru reservoir in Kakinada district, Andhra Pradesh, India, was developed using HEC-HMS version 4.2.1. Daily rainfall and meteorological data from NASA POWER, together with FAO-56 Penman–Monteith potential evapotranspiration, were used to drive the model for the period 2019–2024. The Soil Moisture Accounting (SMA) loss method and the Clark Unit Hydrograph transform were adopted, with model geometry and curve number characteristics derived from a Digital Elevation Model, land use/land cover and hydrologic soil group data in a GIS environment. The model was calibrated against observed daily reservoir inflow for 2019–2022 and validated for 2023–2024, achieving a Nash–Sutcliffe Efficiency (NSE) of 0.117 and 0.170, and a coefficient of determination (R^2) of 0.287 and 0.286, respectively. The model reproduced the calibration-period peak reasonably well but underestimated the major validation-period peak and inflow depth, indicating limited predictive performance rather than strong forecasting skill. Five hypothetical rainfall scenarios, obtained by uniformly scaling the baseline daily rainfall by –30%, –15%, 0%, +15% and +30%, were simulated using the calibrated model to assess the sensitivity of reservoir inflow to rainfall variability. The results show a nonlinear response, with peak reservoir inflow decreasing by 54.51% under the –30% scenario and increasing by 62.41% under the +30% scenario relative to the baseline peak of 723.9 m³/s, while the corresponding simulated inflow depth changed by –84.98% and +203.03%. The study demonstrates a workflow for GIS-based continuous HEC-HMS modelling of a data-limited reservoir catchment and highlights the usefulness of rainfall-scenario simulation for examining potential changes in reservoir inflow relevant to water resources planning.

Keywords: HEC-HMS; rainfall–runoff modelling; reservoir inflow; Soil Moisture Accounting; Clark unit hydrograph; curve number; rainfall scenario analysis; Yeleswaram catchment.

I. INTRODUCTION

A. Background and Motivation

Reliable estimation of catchment runoff and reservoir inflow is central to reservoir operation, flood management and water resources planning, particularly in catchments where continuous long-term streamflow records are limited. Hydrological simulation models allow the rainfall–runoff response of a catchment to be represented physically and used to predict inflow under both historical and hypothetical rainfall conditions.

The Yeleru reservoir, located near Yeleswaram village in Kakinada district, Andhra Pradesh, is an important source of irrigation, drinking water, industrial water supply and groundwater recharge for the region, and its safe and efficient operation depends on a reasonable understanding of the rainfall–runoff behaviour of its contributing catchment. Continuous, GIS-based hydrological modelling studies specifically addressing reservoir inflow in the river basins of coastal Andhra Pradesh remain limited, which motivates the present work.

B. HEC-HMS for Rainfall–Runoff and Reservoir Studies

The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), developed by the US Army Corps of Engineers, is one of the most widely applied tools for rainfall–runoff simulation because it supports both event-based and continuous simulation, is compatible with GIS-derived watershed parameters, and provides a range of loss, transform, baseflow and routing methods suited

to different data availability and modelling objectives. It has been used for event-based and continuous simulation, flood forecasting, reservoir-oriented erosion studies and ensemble-based inflow forecasting in a wide range of catchments, as summarised in the literature review in Section III.

C. Scope of the Present Study

The present study develops a continuous daily HEC-HMS model of the Yeleswaram catchment using publicly available NASA POWER rainfall and meteorological data, calibrates and validates the model against observed daily reservoir inflow, and uses the calibrated model to examine how reservoir inflow responds to a set of hypothetical rainfall-change scenarios. The specific objectives of the study are listed in Section II, the relevant literature is reviewed in Section III, the study area is described in Section IV, and the modelling methodology is presented in Section V.

II. OBJECTIVES OF THE PRESENT STUDY

- 1) To delineate and characterize the Yeleswaram catchment using GIS-based spatial and terrain analysis in ArcGIS.
- 2) To develop a daily rainfall–runoff model for the Yeleswaram catchment using HEC-HMS.
- 3) To calibrate and validate the HEC-HMS model using observed reservoir inflow data for the periods 2019–2022 and 2023–2024, respectively.
- 4) To assess the reservoir inflow response to rainfall variations using selected rainfall scenarios of –30%, –15%, 0%, +15%, and +30%.
- 5) To evaluate the changes in peak reservoir inflow and simulated inflow depth under the selected rainfall scenarios.

III. LITERATURE REVIEW

Choudhari, Panigrahi and Paul [1] applied the HEC-HMS model to the Balijore Nala watershed in Odisha, India, to simulate the rainfall–runoff process. The study used the SCS Curve Number method for estimating rainfall losses and the SCS Unit Hydrograph method for transforming excess rainfall into runoff. The model was calibrated and validated using observed hydrological data, demonstrating the applicability of HEC-HMS for watershed-scale rainfall–runoff simulation. This study provides a useful methodological basis for the present work, although the current study adopts a continuous daily modelling approach using the Soil Moisture Accounting method rather than an event-based SCS-CN approach.

Chatterjee et al. [2] investigated hydrological modelling using HEC-HMS for the Damodar Basin in India. Their study focused on continuous hydrological simulation and included model calibration and sensitivity analysis of important hydrological parameters. The work demonstrated the usefulness of HEC-HMS for representing rainfall–runoff processes over extended periods and highlighted the importance of appropriate parameter selection and calibration. This continuous modelling approach is particularly relevant to the present study, which uses daily rainfall and evapotranspiration data for the 2019–2024 period.

De Silva, Weerakoon and Herath [3] compared event-based and continuous flow hydrograph modelling using HEC-HMS for the Kelani River Basin in Sri Lanka. The study examined different modelling approaches for representing watershed runoff under varying hydrological conditions. The authors demonstrated that model formulation and the choice of loss and transformation methods influence the simulated hydrograph response. Their work supports the use of continuous HEC-HMS modelling when long-term rainfall and streamflow records are available, which is the approach adopted for the Yeleswaram catchment in the present study.

Oleyiblo and Li [4] applied HEC-HMS for flood forecasting in the Misai and Wan'an catchments in China. The study evaluated the capability of the model to reproduce flood hydrographs using rainfall and hydrological observations. The results showed that HEC-HMS can be applied for rainfall-based flood simulation when suitable basin and meteorological inputs are available. The study is relevant to the present work because reservoir inflow response and peak-flow behaviour are also evaluated using observed and simulated hydrographs.

Sardar et al. [5] investigated hydrological modelling for identifying critical erosion-prone areas in the Barakar Basin. Their study demonstrated the importance of spatial watershed characteristics and hydrological modelling in understanding runoff-related processes and supporting reservoir management. Although the modelling framework used in this study was different from HEC-HMS, the work emphasizes the importance of integrating watershed characteristics with hydrological analysis. This supports the GIS-based catchment characterization undertaken in the present study.

Yang and Yang [6] investigated uncertainty in reservoir inflow forecasting using ensemble precipitation forecasts and HEC-HMS. Their work highlighted the influence of precipitation inputs on simulated reservoir inflow and demonstrated the importance of considering rainfall uncertainty in reservoir inflow prediction. The study is particularly relevant to the present work because the Yeleswaram study evaluates how systematic changes in rainfall magnitude affect simulated reservoir inflow and peak-flow response.

Odey and Cho [7] reviewed event-based and continuous hydrological modelling applications using HEC-HMS, with emphasis on modelling approaches, parameterization and performance evaluation. The review highlighted that the selection between event-based and continuous modelling depends on the objectives of the study, available data and the hydrological processes that need to be represented. The review supports the selection of a continuous modelling framework for the present study, where daily rainfall, evapotranspiration and observed reservoir inflow are available for multiple years.

Labade et al. [8] presented a recent comprehensive review of rainfall–runoff modelling using HEC-HMS and discussed the application of different loss, transformation and routing methods in hydrological studies. The review indicates that HEC-HMS provides a flexible framework for representing rainfall–runoff processes under different watershed conditions. The findings support the application of HEC-HMS in the present study and provide a broader methodological background for combining GIS-based watershed characterization, continuous rainfall–runoff simulation and rainfall scenario analysis.

A further literature study on the application of HEC-HMS for event- and continuous-based hydrological modelling [9] reviewed several case studies and the calibration techniques adopted in each, concluding that HEC-HMS performs satisfactorily for event-based runoff simulation and that careful calibration significantly improves model accuracy. This reinforces the calibration and validation procedure, against observed reservoir inflow for 2019–2022 and 2023–2024, adopted for the Yeleswaram catchment in the present study.

A broader state-of-the-art review of hydrological models and HEC-HMS applications [10] compared HEC-HMS with other watershed and reservoir modelling tools and noted that integrating GIS-based terrain, land use and soil analysis with HEC-HMS improves both model accuracy and computational efficiency. This finding directly supports the GIS-based delineation, curve-number estimation and time-of-concentration analysis carried out for the Yeleswaram catchment in Section IV and Section V of the present study.

These studies confirm that HEC-HMS is a well-established and flexible tool for both event-based and continuous rainfall–runoff simulation, and that careful calibration against observed flow or inflow data is essential for reliable performance, particularly when a single parameter set must reproduce runoff behaviour across a wide range of flow conditions. This review also indicates that continuous, GIS-based HEC-HMS applications combined with rainfall-scenario sensitivity analysis for reservoir catchments in coastal Andhra Pradesh remain limited, which is the gap addressed in the present study.

IV. STUDY AREA

The Yeleswaram catchment is the contributing drainage area of the Yeleru reservoir, situated across the Yeleru River near Yeleswaram village and mandal in Kakinada district (formerly part of East Godavari district), Andhra Pradesh, India, at approximately 17.317° N and 82.074° E. The GIS-delineated catchment area used for this study is 2378.03 km². The region experiences a tropical monsoon climate with hot summers, mild winters and seasonal rainfall received mainly during the southwest and northeast monsoons, with an average annual rainfall in the range of 1000–1200 mm; NASA POWER daily rainfall for the 2019–2024 simulation period gives a mean annual rainfall of 1368.85 mm for the catchment. The terrain is predominantly undulating, comprising agricultural land, forest and scattered settlements, with sandy loam, loam and clayey soils of varying infiltration characteristics. The Yeleru reservoir serves as a major source of irrigation, drinking water supply, industrial water supply and groundwater recharge for the region, which motivates the assessment of its inflow behaviour under both historical and hypothetical rainfall conditions.

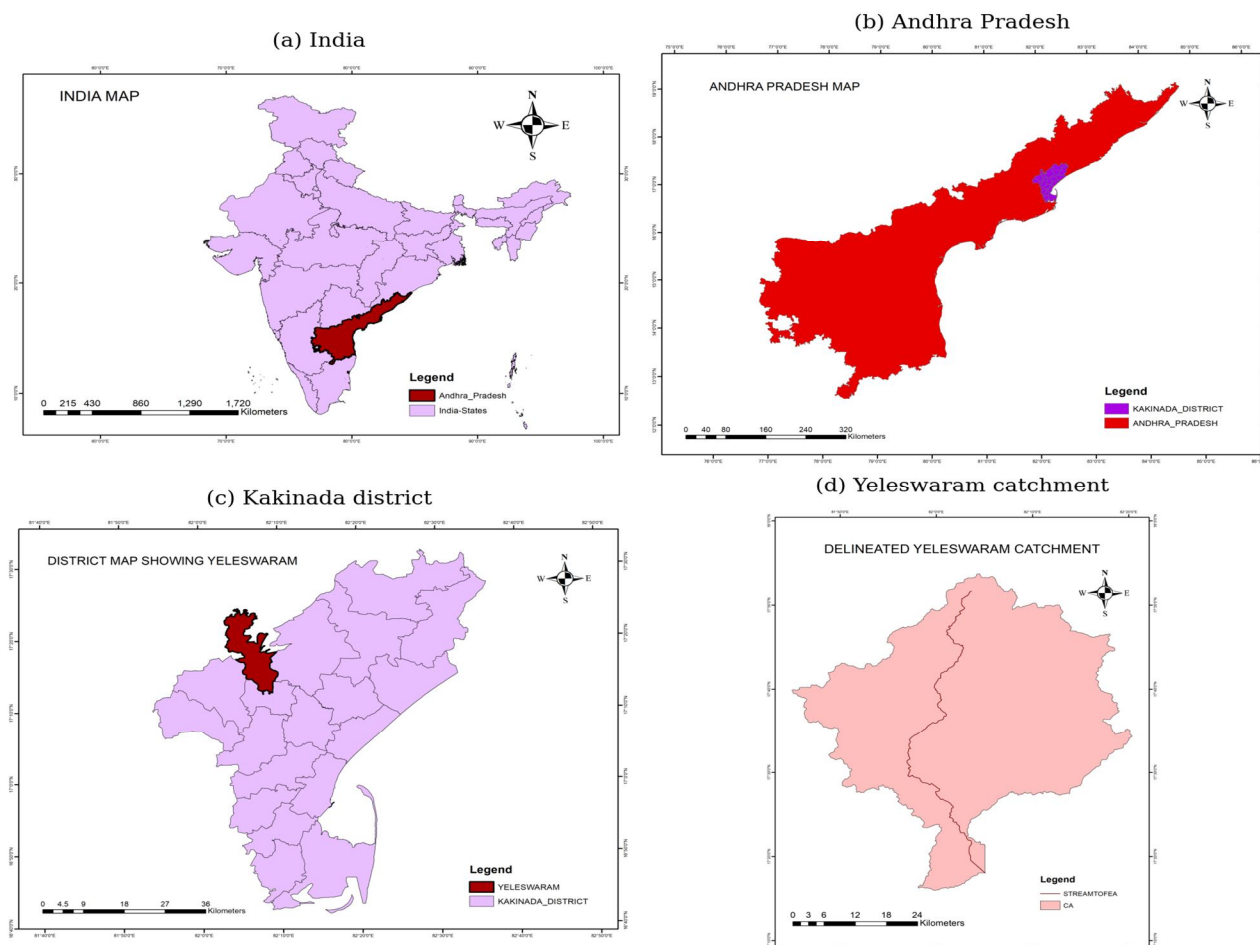


Fig. 1. Location of the study area: (a) India, (b) Andhra Pradesh with Kakinada district highlighted, (c) Kakinada district with the Yeleswaram catchment area highlighted, and (d) the GIS-delineated Yeleswaram catchment boundary and main stream. Selected salient features of the Yeleru reservoir project, as recorded in the project design documents, are summarised in Table I; these values, based on the original project design catchment area, are reported for context alongside the GIS-derived catchment characteristics used for the hydrological modelling in this study.

TABLE I
SALIENT FEATURES OF THE YELERU RESERVOIR PROJECT

Parameter	Value
Design catchment area	2232 km ²
Weighted annual rainfall (design record)	1183 mm
Full reservoir level (FRL)	+86.56 m
Gross storage capacity at FRL	682.70 Mm ³ (24.11 TMC)
Live storage (MDDL–FRL)	508.30 Mm ³ (17.95 TMC)
Maximum designed flood discharge	8070 m ³ /s
Maximum observed flood discharge	5987 m ³ /s

The physiographic and land-surface characteristics of the GIS-delineated catchment, used directly for HEC-HMS parameterisation, are illustrated in Fig. 2.

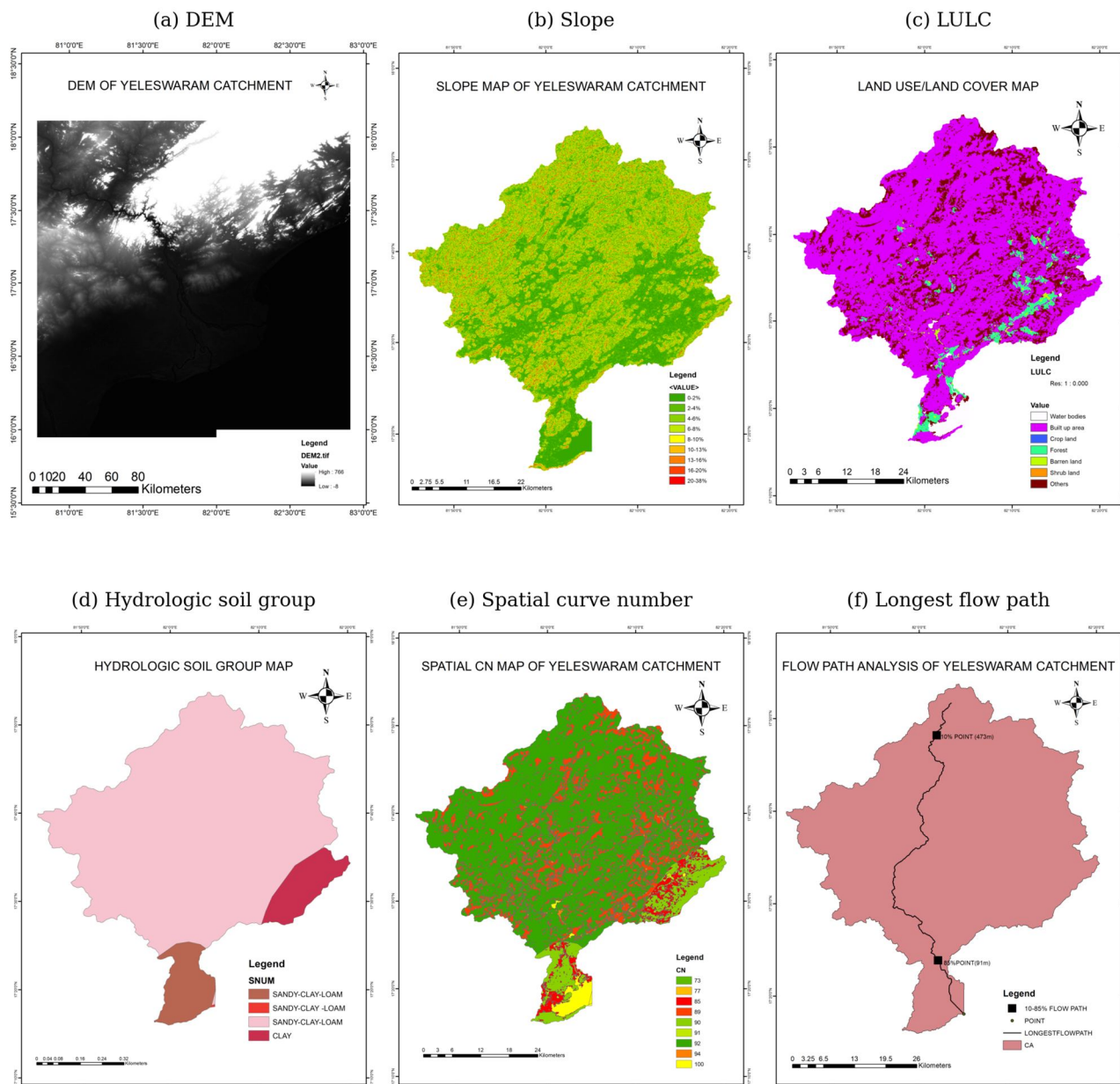


Fig. 2. Catchment characteristics of the Yeleswaram catchment derived in GIS: (a) Digital Elevation Model (SRTM 30 m), (b) slope, (c) land use/land cover (LULC), (d) hydrologic soil group (HSG), (e) spatial curve number (CN), and (f) longest flow path with the 10% and 85% elevation points used for time-of-concentration estimation.

V. METHODOLOGY

The methodology adopted in this study combines GIS-based catchment characterisation with continuous HEC-HMS rainfall-runoff simulation and a subsequent rainfall-scenario sensitivity analysis. Terrain, land use/land cover and soil data were first processed in ArcGIS 10.8 to delineate the Yeleswaram catchment and derive the physical parameters required for curve-number estimation and time-of-concentration analysis. Daily rainfall and meteorological data from NASA POWER were then prepared in HEC-DSSVue and used, together with FAO-56 Penman-Monteith potential evapotranspiration, to drive a continuous HEC-HMS basin model based on the Soil Moisture Accounting loss method and the Clark Unit Hydrograph transform.

The resulting model was calibrated and independently validated against observed daily reservoir inflow, after which the calibrated parameters were held fixed while the input rainfall series was systematically scaled to generate five rainfall scenarios, allowing the corresponding changes in peak reservoir inflow and simulated inflow depth to be quantified. The overall methodology, from data collection through to rainfall-scenario simulation, is summarised in Fig. 3, and each stage is described in detail in the subsections that follow.

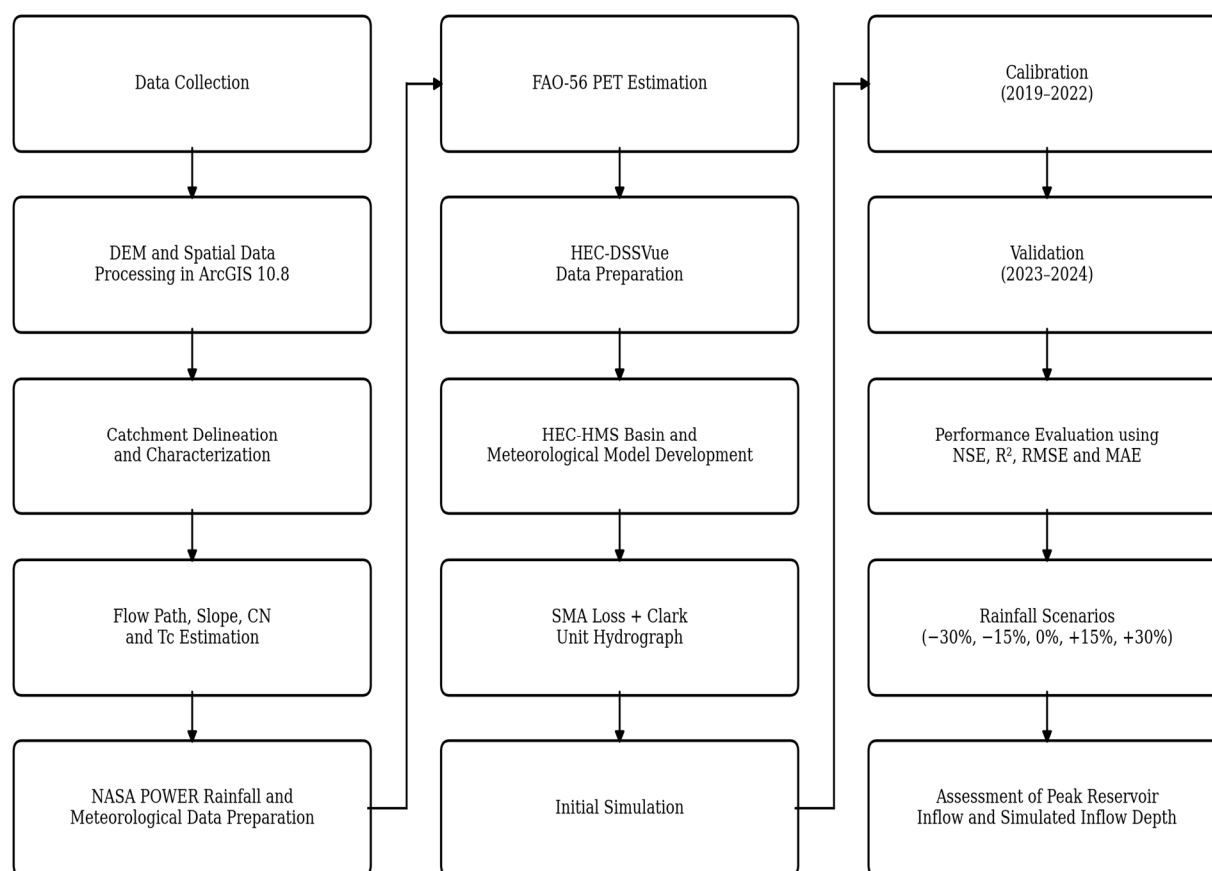


Fig. 3. Overall methodology adopted for HEC-HMS-based rainfall-runoff and reservoir inflow modelling of the Yeleswaram catchment.

A. Data Sources and Input Parameters

The primary data used to configure, calibrate and validate the HEC-HMS model are summarised in Table II. Daily rainfall and meteorological data were obtained from NASA POWER for 2019–2024, and potential evapotranspiration (PET) was estimated from the same data using the FAO-56 Penman–Monteith method [11]. Observed daily reservoir inflow for 2019–2024 was obtained from the Yeleru Reservoir Project Division, Yeleswaram, Kakinada district, and used for model calibration and validation. Catchment terrain was derived from a 30 m SRTM Digital Elevation Model obtained from USGS EarthExplorer, and watershed delineation, longest flow path, centroidal flow path and slope analysis were carried out in ArcGIS 10.8. Land use/land cover was obtained from the ESRI 2021 global land-cover product, and soil information from the FAO Digital Soil Map was used to assign hydrologic soil groups (HSG).

TABLE II
INPUT DATA AND DERIVED HYDROLOGICAL PARAMETERS

Data / parameter	Source / method	Value
Daily rainfall	NASA POWER	2019–2024
Meteorological data	NASA POWER	2019–2024
Potential evapotranspiration	FAO-56 Penman–Monteith	2019–2024
Observed reservoir inflow	Yeleru Reservoir Project Division	2019–2024
Digital Elevation Model	USGS EarthExplorer (SRTM)	30 m
Land use / land cover	ESRI 2021 Land Cover	—
Soil map	FAO Digital Soil Map	—
Catchment area	ArcGIS 10.8 (DEM)	2378.03 km ²
Longest flow path	ArcGIS 10.8	96.168 km
Centroidal flow path	ArcGIS 10.8	56.139 km
10–85% flow length	ArcGIS 10.8	72.126 km
10–85% flow slope	Derived from DEM	27.96 ft/mile
Time of concentration, T _c	GIS-based Clark method	13.22 h
Storage coefficient, R	Model calibration	55 h
Composite curve number, CN	LULC + HSG	89.46

B. Watershed Characterisation and Curve Number

Catchment soils were grouped into hydrologic soil groups C and D, covering 12.15% and 87.85% of the total soil-covered area, respectively, reflecting the moderately to poorly draining soils typical of the region. Seven LULC classes were combined with the two hydrologic soil groups to assign a curve number to each LULC–HSG combination following standard SCS curve-number tables [12]. For each land unit, the accumulated precipitation excess is estimated as

$$P_e = (P - I_a)^2 / (P - I_a + S) \quad (1)$$

where P_e is accumulated precipitation excess, P is accumulated rainfall depth, I_a is the initial abstraction and S is the potential maximum retention. I_a and S are obtained from

$$I_a = 0.2S \quad (2)$$

$$S = (25400 / CN) - 254 \quad (3)$$

For a catchment comprising several LULC–HSG combinations, an area-weighted composite curve number is used:

$$CN = \sum(CN_i \times A_i) / \sum A_i \quad (4)$$

where CN_i and A_i are the curve number and area of the i -th LULC–HSG unit. Applying (4) to the Yeleswaram catchment gives a mean spatial curve number of 89.46, reflecting the predominance of high-runoff-potential built-up and HSG-D areas within the catchment (Fig. 2(c)–(e)).

The time of concentration, T_c , was estimated from the GIS-derived longest flow path and the elevation drop between the 10% and 85% points along that path (Fig. 2(f)) using the Kirpich-type relationship commonly applied in GIS-based watershed characterisation tools,

$$T_c = 0.0078 L^{0.77} S^{-0.385} \quad (5)$$

where L is the 10–85% flow-path length and S is the corresponding flow-path slope, giving $T_c = 13.22$ h for the Yeleswaram catchment. The Clark storage coefficient, R , representing the attenuation of the translated inflow hydrograph by catchment storage [13], was obtained through model calibration against observed reservoir inflow, giving a final value of $R = 55$ h.

C. HEC-HMS Model Setup

The rainfall–runoff model was developed using HEC-HMS version 4.2.1 [14] and configured for continuous daily simulation over the period 1 January 2019 to 31 December 2024. The basin model, named YELESWARAM_BASIN, consisted of a single subbasin, YELESWARAM_SUBBASIN, draining to the outlet YELESWARAM_OUTLET, located at the reservoir inflow point identified in Google Earth Pro and ArcGIS. Because the study required continuous simulation using daily rainfall and evapotranspiration data, the Soil Moisture Accounting (SMA) method was adopted as the loss method, and the Clark Unit Hydrograph method was used to transform excess precipitation into direct runoff. Simple Canopy was used to represent interception storage, while the surface-storage and baseflow methods were set to None. The meteorological model, RAINFALL_2019_2024, used the Specified Hyetograph method for the NASA POWER daily rainfall, prepared in HEC-DSSVue, and the Specified Evapotranspiration method for the daily FAO-56 PET; the same meteorological forcing was used for calibration and validation, and only the rainfall input was subsequently modified for the rainfall-scenario simulations described in Section V-E. The control specification covered the full simulation period at a 1-day computation interval, with calibration performed for 2019–2022 and independent validation for 2023–2024.

The initial parameter values were assigned based on watershed characteristics, model requirements and preliminary simulations. Selected sensitive parameters were subsequently adjusted during calibration against observed reservoir inflow, and the final calibrated values were selected based on improvement in model performance, particularly the Nash–Sutcliffe Efficiency (NSE) and the agreement between observed and simulated hydrographs. The initial and final parameter values, as obtained directly from the calibrated HEC-HMS model, are summarised in Table III.

TABLE III
INITIAL AND CALIBRATED HEC-HMS PARAMETERS

Method	Parameter	Initial	Calibrated
SMA	Max. infiltration (mm/h)	10.0	4.9
SMA	Soil storage (mm)	200	200
SMA	Tension storage (mm)	100	100
SMA	Soil percolation (mm/h)	2.0	0.5
SMA	GW1 storage (mm)	100	100
SMA	GW1 percolation (mm/h)	1.0	1.0
SMA	GW1 coefficient (h)	24	24
SMA	GW2 storage (mm)	50	50
SMA	GW2 percolation (mm/h)	0.5	0.5

Method	Parameter	Initial	Calibrated
SMA	GW2 coefficient (h)	120	120
SMA	Impervious area (%)	0	0
Clark UH	Tc (h)	13.22	13.22
Clark UH	Storage coeff. R (h)	13.22	55
Canopy	Method	Simple Canopy	Simple Canopy
Surface	Method	None	None
Baseflow	Method	None	None

D. Model Performance Evaluation

Model performance was evaluated by comparing observed and simulated daily reservoir inflow using the Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE), defined as

$$NSE = 1 - [\Sigma(O_i - S_i)^2 / \Sigma(O_i - \bar{O})^2] \quad (6)$$

$$RMSE = \sqrt{[\Sigma(O_i - S_i)^2 / n]} \quad (7)$$

$$MAE = (1/n) \Sigma |O_i - S_i| \quad (8)$$

where O_i and S_i are the observed and simulated daily inflow, $\bar{O}$ is the mean observed inflow, and n is the number of daily observations. In addition, the percentage error in peak inflow and in total simulated inflow depth relative to the observed values was computed for the calibration and validation periods.

E. Rainfall Scenario Analysis

To assess the sensitivity of reservoir inflow to changes in rainfall magnitude, five hypothetical rainfall scenarios were developed by uniformly scaling the baseline daily NASA POWER rainfall series for 2019–2024,

$$P_s = P_b(1 + \Delta) \quad (9)$$

where P_s is the scenario rainfall, P_b is the baseline daily rainfall and Δ is the prescribed rainfall change, applied as multipliers of 0.70, 0.85, 1.00, 1.15 and 1.30 corresponding to rainfall changes of –30%, –15%, 0%, +15% and +30% (scenarios S1–S5, Table IV). The calibrated HEC-HMS basin parameters, evapotranspiration input and model configuration were kept unchanged, and only the precipitation input was modified for each scenario. For each scenario, the resulting peak reservoir inflow and total simulated inflow depth were extracted for comparison with the baseline (S3) scenario.

TABLE IV
RAINFALL SCENARIO DEFINITION

Scenario	Change	Multiplier	Condition
S1	–30%	0.70	Dry
S2	–15%	0.85	Mod. dry
S3	0%	1.00	Baseline
S4	+15%	1.15	Mod. wet
S5	+30%	1.30	Wet

VI. RESULTS AND DISCUSSION

A. Rainfall Characteristics

The NASA POWER daily rainfall record for 2019–2024 gives a total catchment rainfall of 8213.10 mm over the six-year period, with a mean annual rainfall of 1368.85 mm (Fig. 4) and a pronounced monsoon concentration between June and October, when average monthly rainfall exceeds 150 mm and peaks in July at about 298 mm (Fig. 5). This seasonal concentration of rainfall is reflected in the corresponding seasonal pattern of observed reservoir inflow discussed in Section VI-B.

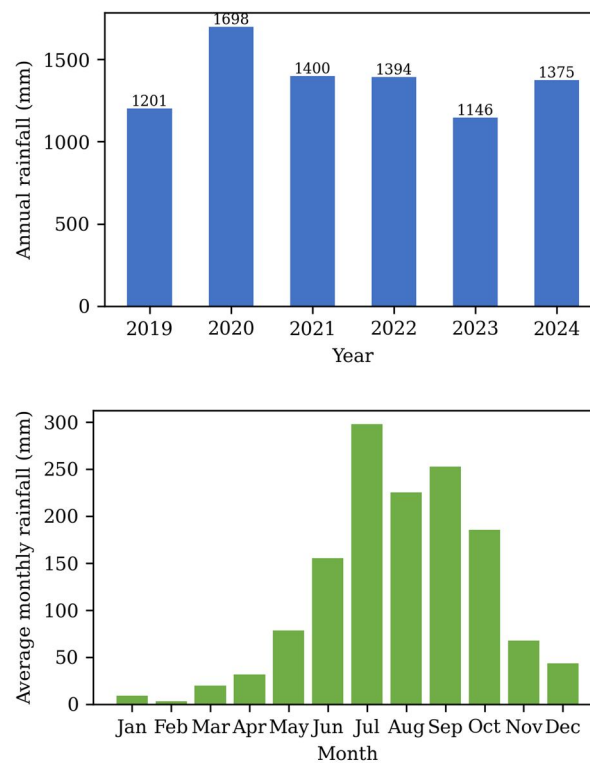


Fig. 4. Annual rainfall (2019–2024) and Fig. 5 average monthly rainfall over the Yeleswaram catchment (NASA POWER).

B. Model Calibration (2019–2022)

The calibrated model achieved an NSE of 0.117 and an R^2 of 0.287 during calibration (Table V), indicating that the simulation provided some predictive information relative to the observed mean-flow benchmark, but with substantial unexplained variance. The RMSE and MAE were $57.56 \text{ m}^3/\text{s}$ and $27.24 \text{ m}^3/\text{s}$, respectively.

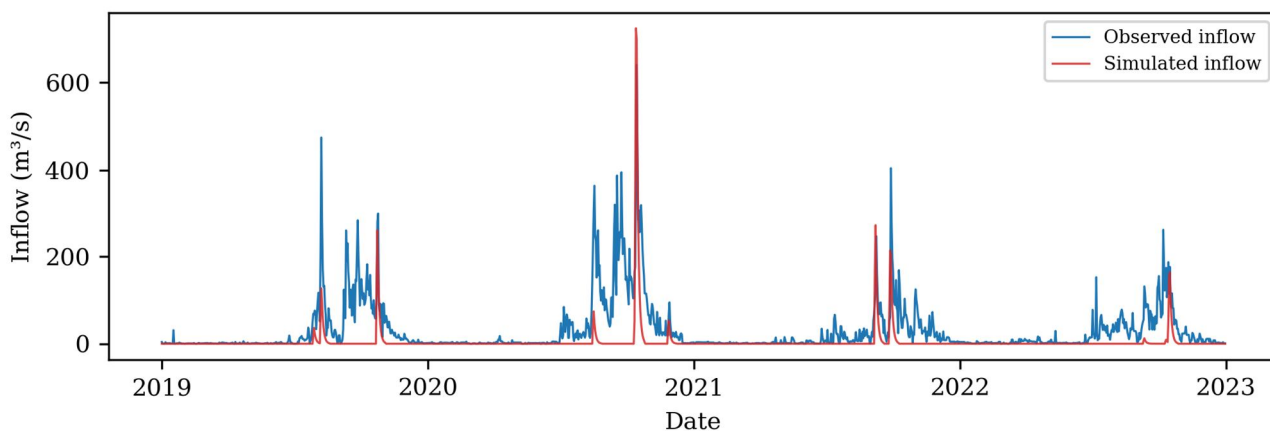


Fig. 6. Observed and simulated daily reservoir inflow during calibration (2019–2022).

The model reproduced the timing and approximate magnitude of the largest calibration-period event, occurring on 14 October 2020, closely: the observed and simulated peaks occurred on the same date, with simulated peak inflow of $682.7 \text{ m}^3/\text{s}$ against an observed peak of $640.4 \text{ m}^3/\text{s}$ (peak error of +6.61%, Fig. 7). However, the total simulated inflow depth over the calibration period (271.27 mm) exceeded the observed inflow depth (163.84 mm) by 65.52%, indicating that the model over-predicted cumulative runoff volume even where individual event peaks were well matched (Fig. 8).

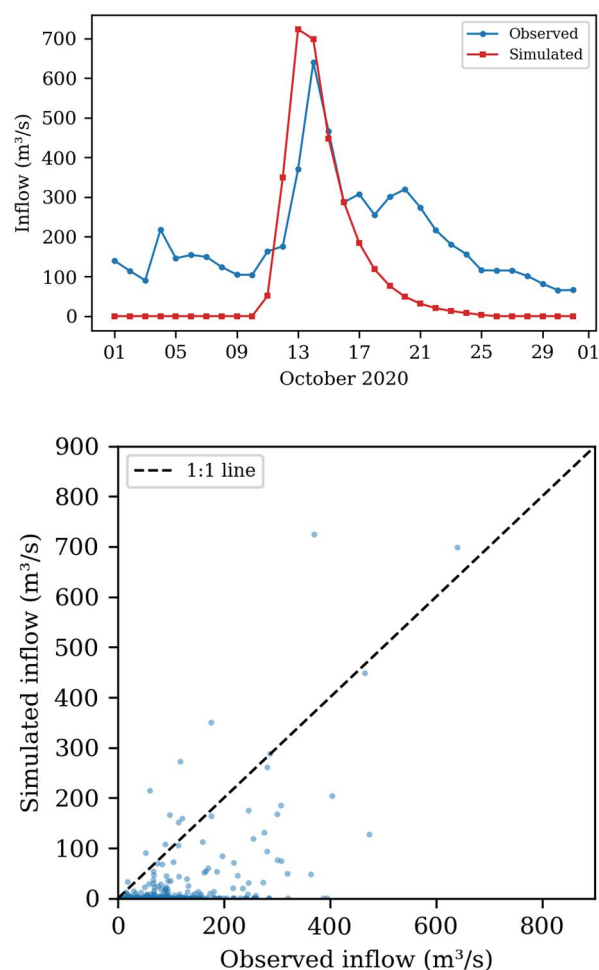


Fig. 7. Observed and simulated inflow for the largest calibration event (October 2020) and Fig. 8 scatter of observed versus simulated daily inflow during calibration.

TABLE V

MODEL PERFORMANCE DURING CALIBRATION AND VALIDATION

Statistic	Calib. (2019–22)	Valid. (2023–24)
NSE	0.117	0.170
R ²	0.287	0.286
RMSE (m³/s)	57.56	52.89
MAE (m³/s)	27.24	23.71
Obs. peak (m³/s)	640.4	841.4
Sim. peak (m³/s)	682.7	392.8
Peak error (%)	+6.61	−53.29
Obs. depth (mm)	163.84	674.58
Sim. depth (mm)	271.27	151.64
Depth error (%)	+65.52	−77.52

C. Model Validation (2023–2024)

During independent validation, the model achieved an NSE of 0.170 and an R^2 of 0.286, with RMSE and MAE of 52.89 m^3/s and 23.71 m^3/s , respectively (Table V). Although these values are marginally higher than the calibration-period statistics, the validation period contained a larger and more rapidly-rising flood event, on 10 September 2024, that the model substantially under-predicted.

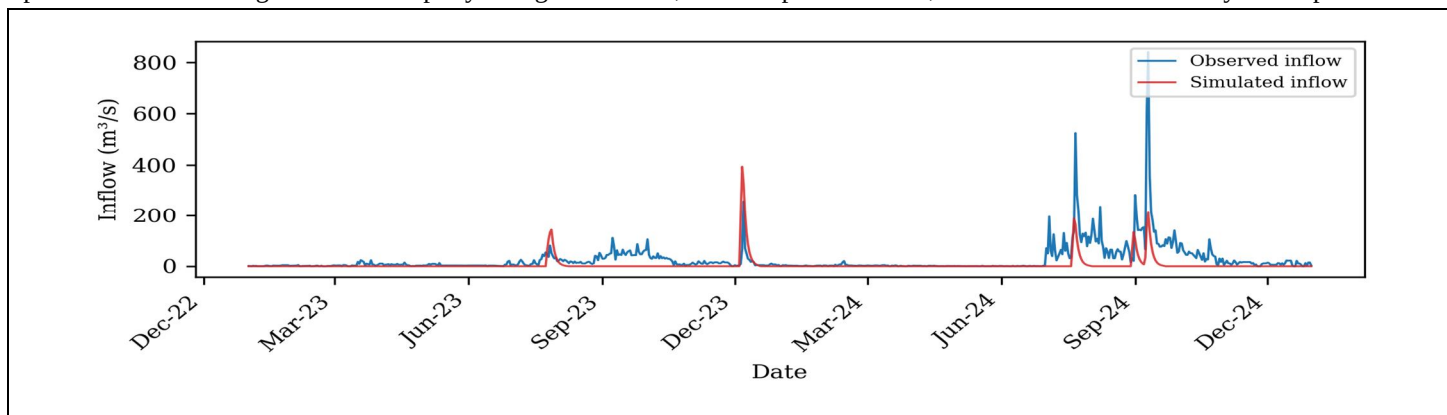


Fig. 9. Observed and simulated daily reservoir inflow during validation (2023–2024).

The simulated peak of 392.8 m^3/s underestimated the observed peak of 841.4 m^3/s by 53.29%, and the simulated peak occurred nearly three months earlier, on 6 December 2023, corresponding to a smaller secondary event rather than the major September 2024 flood (Fig. 10, Fig. 11). The total simulated inflow depth for the validation period (151.64 mm) likewise underestimated the observed inflow depth (674.58 mm) by 77.52%. The relatively low R^2 values and the substantial underestimation of the validation-period peak and inflow depth indicate limitations in reproducing the full magnitude of observed reservoir inflow variability, particularly for the largest events, even though the model achieved positive NSE values in both periods.

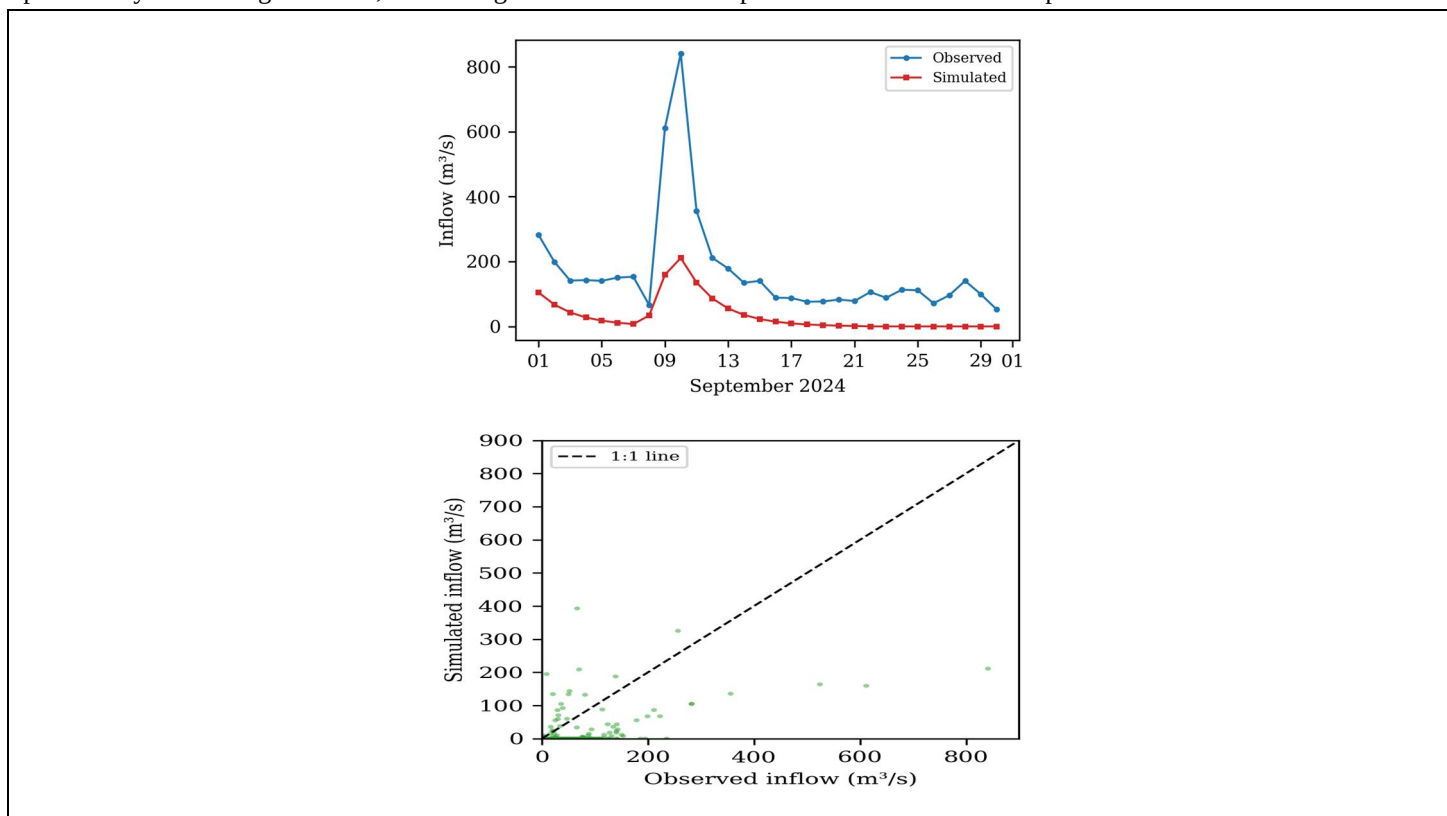


Fig. 10. Observed and simulated inflow for the major validation event (September 2024) and Fig. 11 scatter of observed versus simulated daily inflow during validation.

D. Rainfall Scenario Simulation

The five rainfall scenarios produced total catchment rainfall ranging from 5749.17 mm (S1, -30%) to 10677.03 mm (S5, +30%) over the simulation period, against a baseline (S3) total of 8213.10 mm (Table VI). The results indicate a systematic variation in the total rainfall input with the imposed rainfall scenarios. The lower rainfall scenarios resulted in reduced rainfall availability over the catchment, whereas the increased rainfall scenarios produced progressively higher rainfall inputs compared with the baseline condition.

The simulated reservoir inflow also varied with the change in rainfall input, demonstrating the response of the rainfall-runoff model to different rainfall conditions. The scenario analysis provides an understanding of the possible changes in reservoir inflow under reduced and increased rainfall conditions and can be useful for assessing the sensitivity of the Yeleswaram Reservoir catchment to variations in rainfall.

The comparison of these scenarios provides an indication of the possible range of reservoir inflow response under different rainfall conditions during the study period. This analysis is particularly useful for understanding the effect of rainfall variability on the inflow characteristics of the Yeleswaram Reservoir and provides supporting information for reservoir water management and planning under varying rainfall conditions.

TABLE VI
RAINFALL SCENARIO SIMULATION RESULTS

Scenario	Rainfall change (%)	Total rainfall (mm)	Peak inflow (m ³ /s)	Peak change (%)	Inflow depth (mm)	Depth change (%)
S1	-30	5749.17	329.3	-54.51	63.51	-84.98
S2	-15	6981.14	522.9	-27.78	186.90	-55.79
S3	0	8213.10	723.9	0.00	422.91	0.00
S4	+15	9445.07	926.4	+27.94	758.80	+79.43
S5	+30	10677.03	1175.7	+62.41	1281.43	+203.03

The corresponding simulated peak reservoir inflow decreased to 329.3 m³/s under S1 and 522.9 m³/s under S2, representing reductions of 54.51% and 27.78% relative to the baseline peak of 723.9 m³/s, while peak inflow increased to 926.4 m³/s under S4 and 1175.7 m³/s under S5, increases of 27.94% and 62.41%, respectively (Fig. 12). The simulated inflow depth showed an even more pronounced, nonlinear response, decreasing by 84.98% under S1 but increasing by 79.43% and 203.03% under S4 and S5, respectively, relative to the baseline inflow depth of 422.91 mm (Fig. 13). This disproportionate response in inflow depth compared with peak inflow reflects the nonlinearity of the SCS-based loss method, whereby a given percentage increase in rainfall produces a larger percentage increase in precipitation excess once initial abstraction and infiltration losses are satisfied. These results indicate that, within the range of scenarios examined, increases in rainfall magnitude are likely to produce proportionally larger increases in reservoir inflow volume than in flood peaks, which is a relevant consideration for reservoir operation and water resources planning under wetter or drier future rainfall conditions.

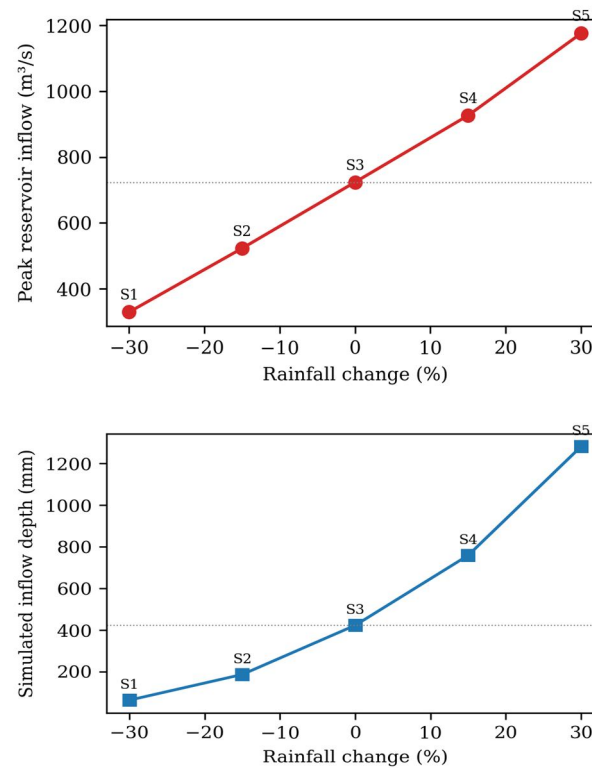


Fig. 12. Simulated peak reservoir inflow under rainfall scenarios S1–S5 and Fig. 13 simulated inflow depth under rainfall scenarios S1–S5, relative to the baseline scenario (S3).

VII. CONCLUSION

A continuous daily rainfall–runoff model of the Yeleswaram catchment (2378.03 km²) was developed in HEC-HMS 4.2.1 using NASA POWER rainfall and meteorological data and FAO-56 Penman–Monteith potential evapotranspiration for 2019–2024, with the Soil Moisture Accounting loss method and Clark Unit Hydrograph transform, and GIS-derived terrain, land use/land cover and hydrologic soil group data used to characterise the catchment and assign a composite curve number of 89.46. The model was calibrated for 2019–2022 and validated for 2023–2024, achieving NSE values of 0.117 and 0.170 and R² values of 0.287 and 0.286, respectively. The model reproduced the calibration-period peak inflow reasonably closely in magnitude and timing but substantially underestimated the major validation-period peak and inflow depth; the model should therefore be characterised as having limited predictive performance for the largest observed events, rather than as a highly accurate reservoir-inflow forecasting tool in its current form. The rainfall-scenario simulations demonstrated a clear, nonlinear sensitivity of reservoir inflow to rainfall magnitude, with peak reservoir inflow ranging from 329.3 m³/s under a –30% rainfall scenario to 1175.7 m³/s under a +30% scenario, compared with a baseline peak of 723.9 m³/s, and an even larger relative change in simulated inflow depth. This scenario analysis illustrates the practical usefulness of the calibrated model for exploring the potential effects of rainfall variability on reservoir inflow, even though further refinement of the calibration would be needed before the model is relied upon for detailed flood-peak forecasting at the Yeleru reservoir.

VIII. ACKNOWLEDGMENT

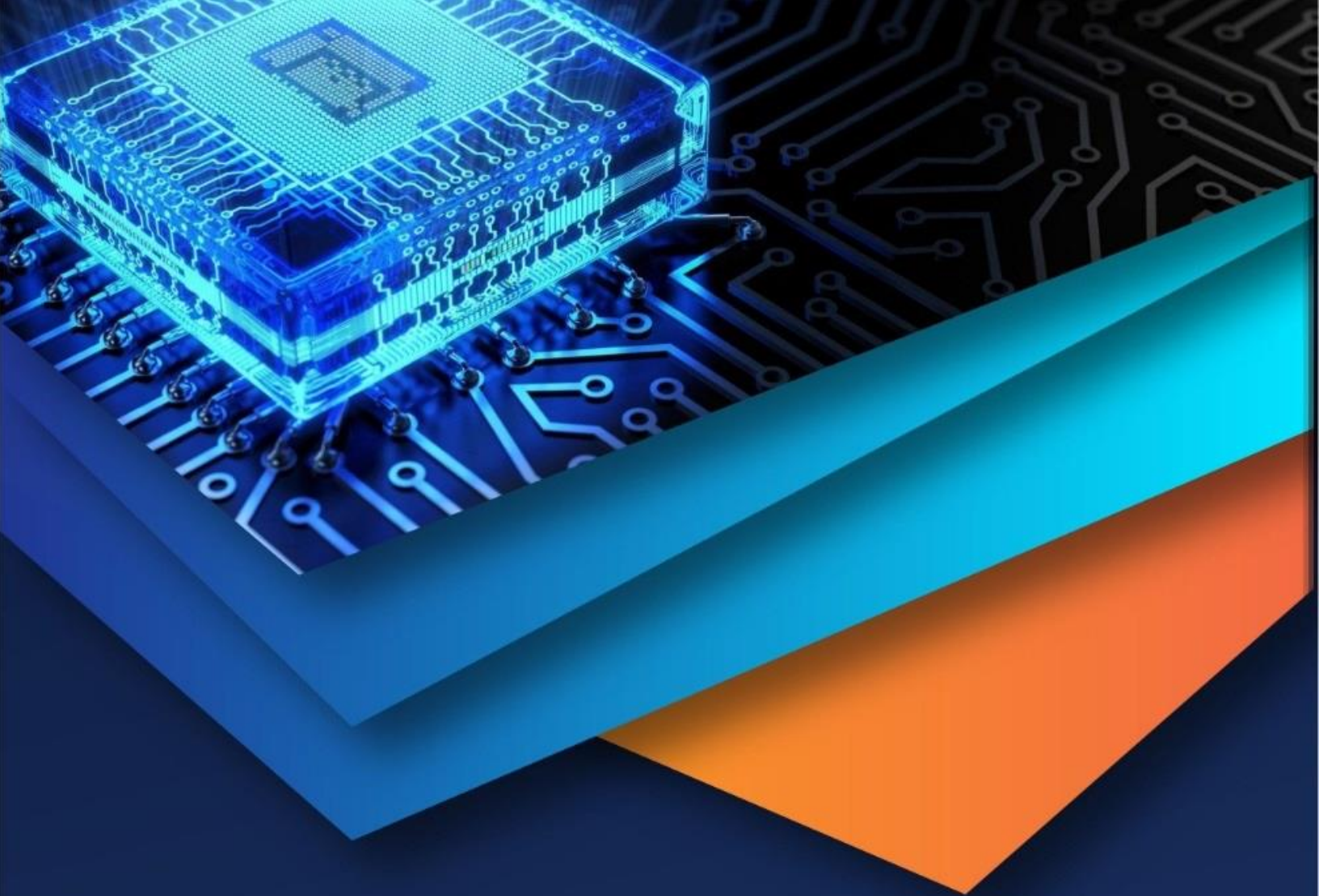
The authors gratefully acknowledge the Yeleru Reservoir Project Division, Yeleswaram, Kakinada district, Andhra Pradesh, for providing observed daily reservoir inflow data, and the Department of Civil Engineering, University College of Engineering Kakinada (A), JNTUK Kakinada, for institutional support during this study.

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