Performance Evaluation of The Pampa Irrigation System in The Ayacut Area Using HEC-HMS, CROPWAT, And Irrigation Performance Indicators

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***Abstract*—Judging a reservoir-based irrigation scheme requires asking whether the water it receives and releases matches what the crops in its command area actually need.**

This study examines the Pampa Irrigation System, a medium irrigation project near Annavaram in Kakinada district, Andhra Pradesh, India, by linking catchment hydrology, crop water demand and comparative performance indicators. The 114.5 km² watershed feeding the reservoir was delineated from a digital elevation model and simulated in HEC-HMS with the SCS Curve Number loss method for the year 2025. The simulation gave a peak discharge of 84.2 m³/s and an annual runoff volume of 146.49 million cubic metres (MCM), equal to 5.173 thousand million cubic feet (TMC); this is 12.23 times the 0.423 TMC gross storage capacity of the reservoir. CROPWAT 8.0 was then applied to paddy in the Kharif (3,694 ha) and Rabi (2,450 ha) seasons of 2025–26. The actual irrigation requirement was 68.1 mm in Kharif and 695.7 mm in Rabi, because effective rainfall fell from 702.0 mm to 70.8 mm.

Relative water supply was 116.64 in Kharif and 22.35 in Rabi, and relative irrigation supply was 186.22 and 31.92, so recorded supply exceeded estimated demand in both seasons. Output per cropped area increased from ₹1,39,071 per ha in Kharif to ₹2,04,733 per ha in Rabi, while output per unit of water consumed was ₹25.97 and ₹26.60 per m³. The results show marked seasonal contrasts and a need to match canal releases to crop demand more closely.

***Index Terms*—CROPWAT, HEC-HMS, Irrigation performance, Pampa ayacut, Relative irrigation supply, Relative water supply, Runoff-to-storage ratio**

I. INTRODUCTION

Irrigation closes the gap between what rainfall supplies and what a crop needs. In a reservoir-fed scheme the quality of that service depends on a chain of linked processes: rain becomes catchment runoff, runoff is stored, stored water is released into canals, and the crop finally uses what reaches the field. A weakness at any link appears as unreliable delivery, wasted water or poor yield [3], [21]. Assessing such a scheme therefore means looking at water availability, crop demand, delivery and productivity together rather than one at a time.

Several frameworks exist for this purpose. Early work organised water-delivery performance around adequacy, efficiency, dependability and equity [1], and later guidelines extended it to a wider set of process and output indicators [3], [4]. A widely used comparative set relates agricultural output to land, water supplied and water consumed, and pairs it with ratios that compare supply with demand [2]. The literature also cautions that a single efficiency figure can mislead, because water lost from one field may be reused elsewhere in the basin [22].

Two modelling tools are commonly used to quantify the hydrological and agronomic sides of the problem. HEC-HMS converts rainfall into runoff for a watershed from its terrain, land cover and soil [15], while CROPWAT estimates evapotranspiration, effective rainfall and irrigation requirements from climate, crop and soil inputs [14]. In practice the two are usually applied in separate studies, so the link between water that a catchment can deliver, water that

crops demand, and water that is actually released is rarely examined in one place.

The Pampa Irrigation System in Kakinada district is a paddy-based medium project whose reservoir is fed by a small hilly catchment. This paper evaluates the system by combining a GIS-supported HEC-HMS runoff simulation, CROPWAT irrigation requirements for the Kharif and Rabi seasons, recorded irrigation supply, and a set of indicators that includes a runoff-to-gross-storage ratio for the reservoir. The aim is to show how water availability, crop demand and delivered supply compare in each season and what this implies for operation of the scheme.

II. OBJECTIVES OF THE PRESENT STUDY

The study was carried out with the following objectives:

1) To delineate the catchment of the Pampa Reservoir with GIS and HEC-HMS and describe its hydrological parameters;
2) to estimate annual runoff volume and peak discharge for 2025 with HEC-HMS and compare the simulated inflow with the recorded inflow;
3) to determine reference evapotranspiration, effective rainfall, crop water requirement and irrigation requirement of paddy in the Kharif and Rabi seasons with CROPWAT 8.0;
4) to relate the HEC-HMS runoff volume to the gross storage capacity of the reservoir through a runoff-to-storage capacity indicator;
5) to compare recorded irrigation supply with estimated demand through relative water supply and relative irrigation supply; and
6) to examine agricultural output in relation to cropped area, command area, water supplied and water consumed.

III. LITERATURE REVIEW

A. Frameworks and indicators for irrigation performance

Molden and Gates proposed that water-delivery systems be assessed through measures of adequacy, efficiency, dependability and equity, and stressed that delivering the right volume is not enough unless it arrives at the right time and place [1]. Bos reviewed indicators for irrigation and drainage and argued that they should be chosen to suit the objectives of a project and built on measurable quantities rather than on one efficiency value [3]; practical guidance for putting this into practice followed in a later manual [4]. Molden et al. then proposed a compact comparative set, relating output to cropped area, command area, supply and consumption alongside supply-to-demand ratios, and showed with 18 systems that performance varied widely between schemes [2]. Elshaikh et al. surveyed more than 70 studies and found that direct indicators, fuzzy and multi-criteria approaches and remote sensing are all in use, with no single method suited to every project [10].

B. Evaluation studies and modelling tools

Bastiaanssen and Bos described how remotely sensed evapotranspiration and crop information can complement canal-flow measurements for indicator calculation over large areas [5]. Ray et al. applied this idea to the Mahi Right Bank Canal command in Gujarat and compared crop water requirement with canal releases at distributary level, finding surplus water in upper sections but weaker crop condition toward the tail [6]. Studies in Rajasthan combined measured outlet discharges with CROPWAT-based demand and rated adequacy, equity and dependability as poor in the Amarpura minor of the Som-Kagdar project [7] and in the Bhimsagar left main canal [8]. In Kerala, Gilsha Bai et al. combined department withdrawal records, field discharge measurements and CROPWAT 8.0 for the Chalakudy River Diversion Scheme and reported an overall conveyance efficiency of about 51% with fair supply indicators [11]. Cakmak et al. showed how benchmarking indicators can rank irrigation schemes in Turkey and point to those needing attention [9]. These studies share a common approach with the present work: crop demand is estimated with a model and compared with the water actually delivered.

On the hydrological side, GIS-based delineation followed by HEC-HMS simulation has been used to represent runoff in the Upper Godavari Basin of Maharashtra [12], and the Curve Number procedure used for losses rests on the SCS method described in standard references [16], [17], [18]. Crop water requirement in this work follows the FAO Penman–Monteith approach [13] implemented in CROPWAT [14]. Reviews of water productivity emphasise that output per unit of water consumed is the more

informative measure when water is scarce [20], [23], and that productivity gains need to be interpreted at basin scale [21], [22].

C. Research gap

Most of the studies above assess delivery performance or hydrology, but seldom both for the same scheme. Few of them place the runoff that a catchment can generate beside the storage capacity of its reservoir, and fewer still relate that to crop demand and to the output of the command area. The present paper addresses this by treating the Pampa system as a connected chain, from catchment runoff to reservoir storage, canal supply, crop demand and output.

IV. METHODOLOGY

A. Study area

The Pampa Reservoir lies across the Pampa River near Annavaram in Sankhavaram Mandal of Kakinada district, Andhra Pradesh, at about 17°33′ N and 82°19′ E (Fig. 1). The river rises near Rallavagu in Routhulapudi Mandal. The project was administratively approved in 1964 and was completed around 1969 to stabilise irrigation for about 12,005 acres (4,858 ha) in Tuni, Sankhavaram and Thondangi Mandals. Water is carried to the ayacut, the area commanded by the canal, through a 12.7 km main canal with a design discharge of 250 cusecs. Paddy is the principal crop in the 13 villages served. Table I lists the salient features of the project.

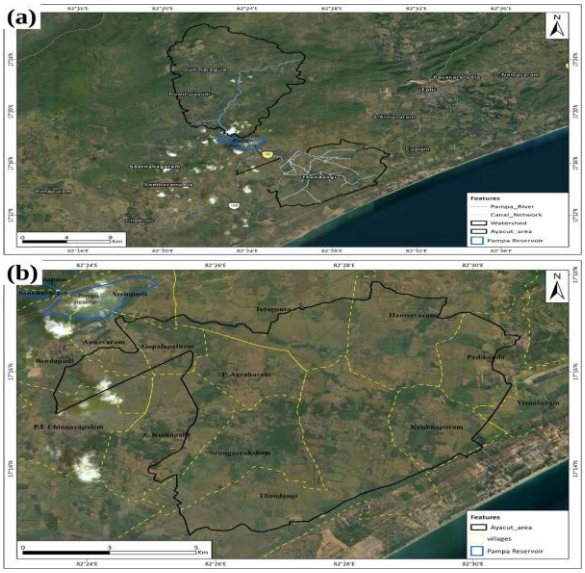


Fig. 1. Pampa Irrigation System: (a) watershed, ayacut and reservoir; (b) village-wise ayacut area.

TABLE I SALIENT FEATURES OF THE PAMPA IRRIGATION SYSTEM

Feature	Value
Location	Annavaram, Sankhavaram Mandal, Kakinada District, A.P.
Coordinates of the project	17°33′00″ N, 82°19′00″ E
Approval / completion	1964 / about 1969
Full reservoir level (FRL)	+32.00 m
Gross storage capacity	0.423 TMC
Spillway	5 vertical gates, 12.2 m × 5.33 m
Maximum flood discharge	49,400 cusecs
Dependable net yield / allocation	1.450 TMC / 1.250 TMC
Main canal length / discharge	12.7 km / 250 cusecs
Ayacut	12,005 acres (4,858 ha), 13 villages
Mandals benefited	Thondangi, Tuni, Sankhavaram
Cropping pattern	Paddy

B. Data and overall approach

Data were grouped as spatial, meteorological, hydrological, crop and irrigation records (Fig. 2). A digital elevation model (DEM, SRTM-based terrain in HEC-HMS) supplied elevation and drainage information, and land use/land cover (LULC) and soil layers were prepared in GIS for the watershed and the ayacut. Rainfall for the simulation came from IMD and NASA POWER sources. Because suitable IMD observations were not available at the ayacut itself, Tuni (17.35° N, 82.50° E, 35 m) was adopted as the representative climate station for CROPWAT, with monthly minimum and maximum temperature, humidity, wind speed, sunshine and rainfall. Over a year the Tuni record averages 20.2 °C minimum and 33.3 °C maximum temperature, 76% humidity, 194 km/day wind run and 6.0 h of sunshine, with 1,554.9 mm of rainfall and a mean ET_0 of 4.22 mm/day (Fig. 4). Irrigated area for 2025–26 was taken from the Directorate of Economics and Statistics, Government of Andhra Pradesh (Table II), and recorded reservoir

levels, storage, inflow and outflow were obtained from the Irrigation Department. Production values by season came from agricultural department records.

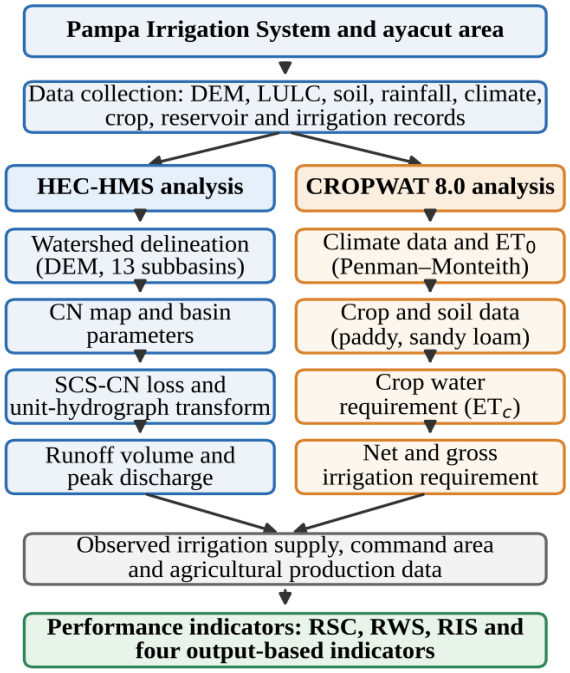


Fig. 2. Overall methodology of the study.

TABLE II SEASON-WISE IRRIGATED AREA OF THE PAMPA AYACUT, 2025–26 (HA)

Season	Sankhavaram	Thondangi	Tuni	Total
Kharif	74	3,085	535	3,694
Rabi	116	2,334	—	2,450

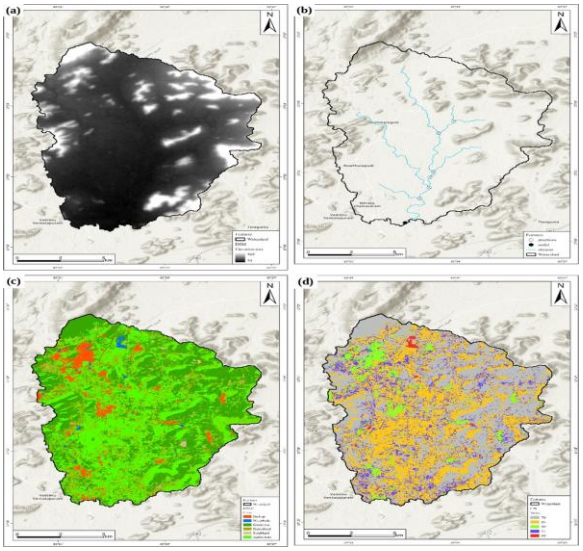


Fig. 3. Spatial inputs for the Pampa watershed: (a) DEM, (b) drainage network, (c) land use/land cover and (d) Curve Number map.

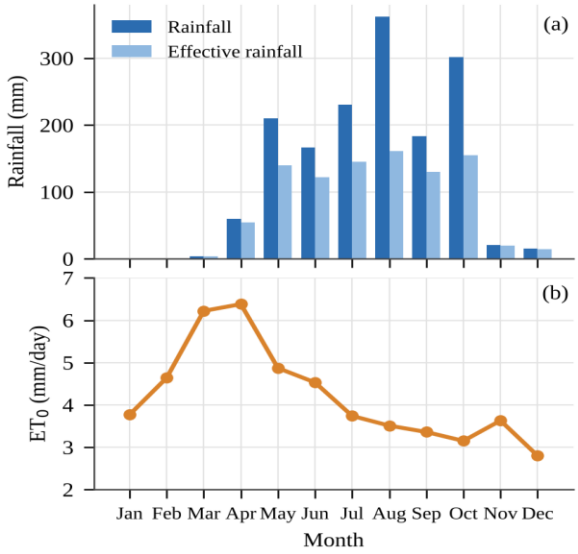


Fig. 4. Climate inputs at Tuni used in CROPWAT: (a) monthly rainfall and effective rainfall; (b) reference evapotranspiration.

C. Rainfall–runoff modelling with HEC-HMS

1) Basin model. The contributing watershed was delineated from the DEM in HEC-HMS, giving 13 subbasins, six reaches and a single outlet (Fig. 5). The watershed area is the sum of the subbasin areas:

$$A_{total} = \sum_{i=1}^{n} A_i \qquad (1)$$

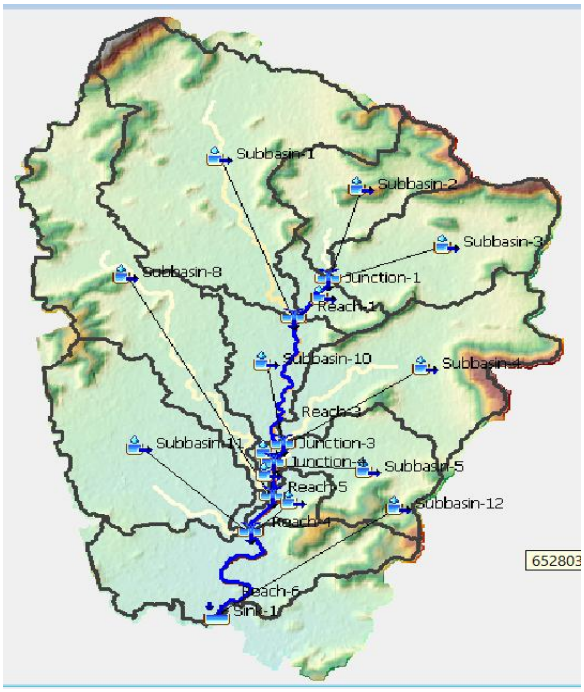


Fig. 5. HEC-HMS basin model of the Pampa watershed showing subbasins, reaches, junctions and the outlet (Sink-1).

where A_i is the area of subbasin i and n is the number of subbasins (n = 13). The total area was 114.5 km².

$$S = \frac{25400}{CN} - 254 \quad (2)$$

$$I_a = 0.2S \quad (3)$$

$$Q = \frac{(P-I_a)^2}{P-I_a+S} \quad (4)$$

2) Curve Number and loss method. LULC and soil layers were overlaid in ArcGIS, hydrologic soil groups were assigned, and a Curve Number (CN) was attached to every land-use and soil combination to produce the CN map (Fig. 3d). Mean subbasin CN ranged from 80.7 to 84.1. Losses were computed with the SCS Curve Number method. The maximum potential retention S (mm) follows from CN, the initial abstraction I_a (mm) is taken as a fixed fraction of S, and direct runoff depth Q (mm) from a storm depth P (mm) is obtained as

with Q = 0 whenever P ≤ I_a.

$$T_L = 0.6T_c \quad (5)$$

3) Transform and routing. Excess rainfall was converted to a runoff hydrograph with the selected transform method, which follows the unit-hydrograph concept and uses the lag time T_L of each subbasin. The lag time was taken as 60% of the time of concentration T_c, which HEC-HMS derives from the longest flow path and slope of the subbasin:

The subbasin parameters are listed in Table III.

$$V \approx \sum_{i=1}^{N} Q_i \Delta t \quad (6)$$

$$V_{TMC} = \frac{V_{m^3}}{28{,}316{,}846.592} \quad (7)$$

TABLE III SUBBASIN PARAMETERS OF THE PAMPA WATERSHED

Sub-basin	CN	L (km)	Slope (%)	T_c (h)	T_L (min)	S (mm)	I_a (mm)
1	83.47	13.06	14.70	2.49	89.7	50.3	10.1
2	80.66	5.97	24.90	1.12	40.4	60.9	12.2
3	80.74	7.06	16.38	1.58	56.8	60.6	12.1
4	81.23	9.24	15.51	1.98	71.3	58.7	11.7
5	81.51	5.68	15.35	1.34	48.1	57.6	11.5
6	83.75	1.34	4.12	0.75	27.2	49.3	9.9
7	83.42	3.60	13.63	0.92	33.3	50.5	10.1
8	83.45	15.78	13.46	3.03	109.2	50.4	10.1
9	83.08	3.00	12.31	0.85	30.6	51.7	10.3
10	84.00	5.66	5.41	2.07	74.5	48.4	9.7
11	83.55	8.59	7.99	2.41	86.8	50.0	10.0
12	84.08	6.57	12.16	1.55	55.8	48.1	9.6
13	80.89	1.05	3.69	0.72	26.0	60.0	12.0

CN: mean Curve Number; L: longest flow path; T_c: time of concentration; T_L: lag time; S: maximum potential retention; I_a: initial abstraction.

D. Crop water requirement with CROPWAT 8.0

CROPWAT 8.0 was set up for paddy for two seasons: Kharif (planting 2 June, harvest 29 October 2025) and Rabi (planting 1 December, harvest 29 April). Crop and soil inputs are given in Table IV. The calculation sequence is climate data, ET_0, crop evapotranspiration, effective rainfall, irrigation requirement and schedule.

TABLE IV CROP AND SOIL INPUTS USED IN CROPWAT

Parameter	Value
Crop	Paddy (rice)
Growth stages (initial/development/mid/late)	30 / 30 / 60 / 30 days
Total crop period	150 days
K_c at mid-season / at end	1.20 / 0.90
Depletion fraction	0.20
Kharif period	2 June – 29 October
Rabi period	1 December – 29 April
Soil texture	Sandy loam

Parameter	Value
Total available water	130 mm/m
Maximum rain infiltration	35 mm/day
Initial soil moisture depletion	50% (65 mm/m)
Irrigation timing / refill	At 100% depletion / to field capacity
Field efficiency	70%

1) Reference evapotranspiration. ET_0 (mm/day) was computed with the FAO Penman–Monteith equation [13],

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (8)$$

in which Δ is the slope of the vapour-pressure curve (kPa/°C), R_n the net radiation and G the soil heat flux (both MJ/m²/day), γ the psychrometric constant (kPa/°C), T the mean air temperature (°C), u_2 the wind speed at 2 m (m/s), and e_s and e_a the saturation and actual vapour pressures (kPa).

2) Crop evapotranspiration and effective rainfall. Crop evapotranspiration ET_c (mm/day) is the product of ET_0 and the stage-dependent crop coefficient K_c. Effective rainfall P_e (mm) was calculated from monthly rainfall P (mm) with the USDA Soil Conservation Service method,

$$ET_c = K_c \times ET_0 \quad (9)$$

$$P_e = P\frac{125 - 0.2P}{125}, \ P \le 250\ mm \quad (10)$$

$$P_e = 125 + 0.1P, \ P > 250\ mm \quad (11)$$

3) Irrigation requirement. The net irrigation requirement (NIR) is the crop water requirement (CWR) that rainfall does not meet, and the gross irrigation requirement (GIR) divides it by the field application efficiency E_a (decimal, 0.70 here):

$$NIR = CWR - P_e \quad (12)$$

$$GIR = \frac{NIR}{E_a} \quad (13)$$

E. Irrigation performance indicators

Seven indicators were used. The first relates the HEC-HMS runoff to the reservoir; the next four are the comparative output indicators of Molden et al. [2], computed from the production value PV (₹), the irrigated cropped area A_c (ha), the command area A_{cmd} (ha, 4,858.4 ha), the volume of irrigation supplied V_s (m³) and the volume of water consumed by evapotranspiration V_{ET} (m³); the last two compare supply with demand.

1) Runoff-to-storage capacity ratio. This indicator expresses the annual HEC-HMS runoff volume V_{sim} as a multiple of the gross storage capacity S_g of the reservoir (both in TMC):

$$RSC = \frac{V_{sim}}{S_g} \quad (14)$$

2) Output indicators. Output per cropped area (O_c), per unit command area (O_a), per unit irrigation supply (O_s) and per unit water consumed (O_w) are

$$O_c = \frac{PV}{A_c} \quad (15)$$

$$O_a = \frac{PV}{A_{cmd}} \quad (16)$$

$$O_s = \frac{PV}{V_s} \quad (17)$$

$$O_w = \frac{PV}{V_{ET}} \quad (18)$$

where $V_{ET} = 10 \cdot ET_c \cdot A_c$ when ET_c is the seasonal crop evapotranspiration in mm and A_c is in ha.

3) Supply-to-demand ratios. Relative water supply (RWS) compares the total water supply with the crop water demand, and relative irrigation supply (RIS) compares irrigation supply with the irrigation requirement.

A value near 1 indicates supply matched to demand, values below 1 indicate shortage, and values above 1 indicate surplus:

$$RWS = \frac{Total\ water\ supply}{Crop\ water\ demand} \quad (19)$$

$$RIS = \frac{Irrigation\ supply}{Irrigation\ requirement} \quad (20)$$

V. RESULTS AND DISCUSSION

A. Simulated runoff of the Pampa watershed

For 2025 the HEC-HMS model gave, at the outlet (Sink-1) draining 114.5 km², a peak discharge of 84.2 m³/s on 17 August 2025 (24:00 h) and a total runoff volume of 146.4863 MCM, or 5.173 TMC (Table V).

The hydrograph in Fig. 6 shows no flow until about April, then a sequence of short, sharp peaks through the monsoon months.

The largest event in August is followed by a group of events in late October with peaks up to about 58 m³/s. This flashy response is consistent with the short times of concentration (0.72–3.03 h) and the steep slopes (up to 24.9%) of the subbasins in Table III.

Each of the hydrograph's peaks corresponds to a rainfall event, so the annual volume is made up of many separate inflows rather than one flood.

TABLE V HEC-HMS RESULTS AT THE WATERSHED OUTLET, 2025

Parameter	Result
Simulation period	1 Jan – 31 Dec 2025
Drainage area	114.5 km²
Peak discharge	84.2 m³/s
Time of peak	17 Aug 2025, 24:00 h
Total runoff volume	146.4863 MCM = 5.173 TMC

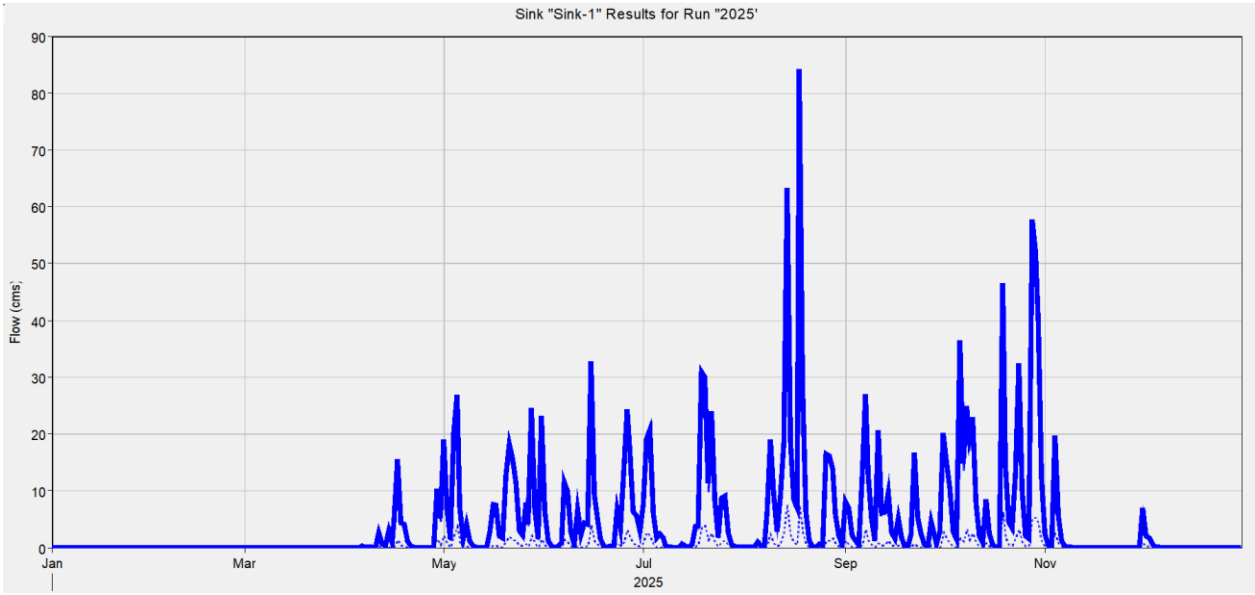


Fig. 6. Simulated runoff hydrograph at the Pampa watershed outlet (Sink-1) for 2025 (flow in m³/s).

B. Comparison with recorded inflow

Monthly HEC-HMS discharges (m³/s) were converted to cusecs with the factor 35.3147 and set beside the inflow recorded for the reservoir (Fig. 7). Summed over the year, the simulated values total 59,858 against 35,532 for the recorded inflow, a ratio of 1.68. The two series agree in timing: both are zero from January to March, both rise from April and both reach their highest value in October, and the correlation between the twelve-monthly pairs is 0.90. The model is, however, higher than the record from May to September, when it responds more strongly to early-season rain, and lower in November and December. The model was not calibrated or validated, so this gap is expected. Other likely contributors are rainfall variability across the watershed, the loss parameters adopted, and the fact that recorded inflow is itself derived from reservoir level and storage readings. Expressed over the watershed, the simulated volume corresponds to a depth of about 1,280 mm, which is of the order of the 1,554.9 mm annual rainfall at Tuni and supports the reading that the uncalibrated model tends to over-predict runoff. Calibration against continuous inflow records, with the goodness-of-fit statistics recommended in [19], is the natural next step.

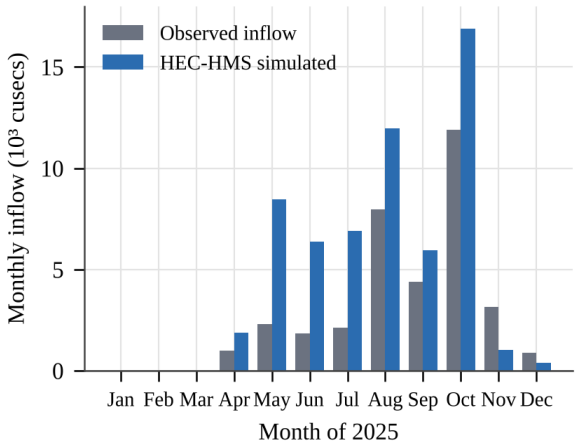


Fig. 7. Monthly recorded inflow and HEC-HMS simulated inflow of the Pampa Reservoir, 2025.

C. Runoff-to-storage capacity ratio

Dividing the simulated annual runoff of 5.173 TMC by the gross storage capacity of 0.423 TMC gives an RSC of 12.23 (Fig. 8). In other words, the catchment generated about twelve times the volume that the reservoir can hold. Recorded surplus releases in August, September and October 2025 (1,530, 1,120 and 7,900 cusecs) confirm that the reservoir filled and spilled during the monsoon. The result suggests that the limiting factor for irrigation at Pampa is the small storage rather than the yield of the catchment, and that carry-over of monsoon water into the dry season depends on the operating rules more than on rainfall alone.

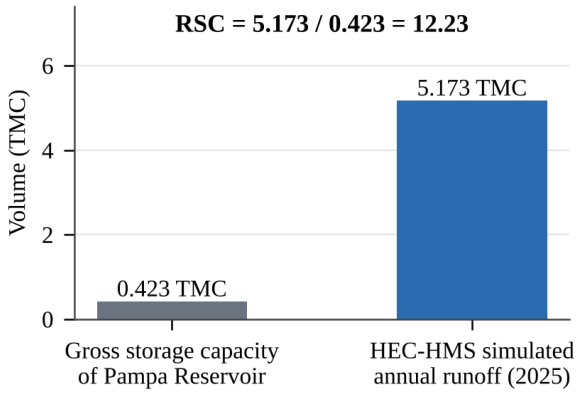


Fig. 8. Runoff-to-storage capacity indicator: HEC-HMS simulated runoff compared with the gross storage capacity of the Pampa Reservoir.

D. Crop water and irrigation requirements

The CROPWAT results are summarised in Table VI and Fig. 9. Kharif paddy had a crop evapotranspiration of 535.5 mm, which monsoon rainfall nearly covered: the decade-wise requirement table credits 702.0 mm of effective rainfall and returns no irrigation requirement. The soil-water-balance schedule, which accounts for storage and losses in more detail, credits 464.4 mm of effective rainfall and leaves an actual irrigation requirement of 68.1 mm, supplied by five applications totalling 179.7 mm gross (125.7 mm net). Rabi paddy used 769.6 mm of crop evapotranspiration against only 70.8 mm of effective rainfall, so the irrigation requirement was 696.1 mm in the requirement table and 695.7 mm in the schedule; the schedule needed 27 applications totalling 1,060.2 mm gross (741.9 mm net) (Fig. 10). Estimated yield reduction was only 0.2% in Kharif and 0.1% in Rabi, which means that the schedules meet crop demand almost fully.

TABLE VI CROPWAT 8.0 RESULTS FOR PADDY IN THE PAMPA AYACUT

Parameter	Kharif	Rabi
Area (ha)	3,694	2,450
Crop evapotranspiration (mm)	535.5	769.6
Effective rainfall, CWR table (mm)	702.0	70.8
Irrigation requirement, CWR table (mm)	0.0	696.1
Schedule: gross irrigation (mm)	179.6	1,060.0
Schedule: net irrigation (mm)	125.8	742.0
Actual irrigation requirement (mm)	68.1	695.7
Actual / potential crop water use (mm)	531.2 / 532.5	763.0 / 763.8
Yield reduction (%)	0.2	0.1
Gross volume, MCM (TMC)	6.638 (0.234)	25.975 (0.917)
Net volume, MCM (TMC)	4.643 (0.164)	18.177 (0.642)

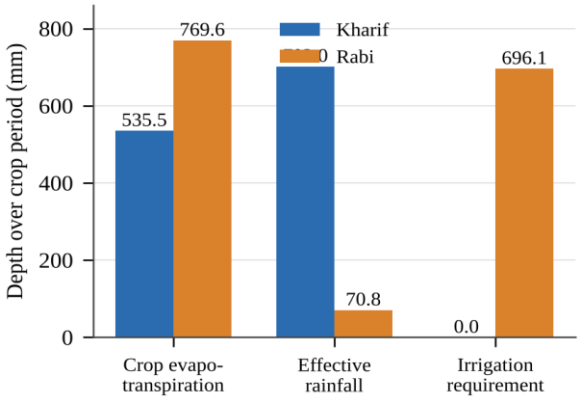


Fig. 9. Seasonal crop water balance of paddy from CROPWAT 8.0.

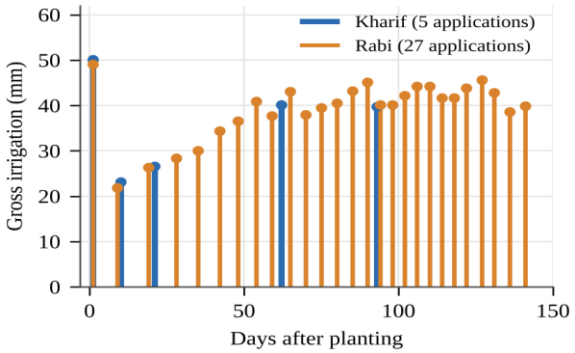


Fig. 10. Gross irrigation applied at each event of the CROPWAT schedules.

Although the Rabi area is a third smaller, Rabi demand is far greater. The gross requirement per hectare in Rabi (1,060.2 mm) is 5.9 times that of Kharif (179.7 mm), and the Rabi volume of 25.975 MCM is 3.9 times the Kharif volume of 6.638 MCM. Thondangi Mandal accounts for most of the demand in both seasons, with 5.544 MCM in Kharif and 24.745 MCM in Rabi. For a reservoir whose dependable yield is 1.450 TMC and allocation is 1.250 TMC, the Rabi gross requirement of 0.917 TMC alone is a large share of the water available.

E. Agricultural output indicators

The production value of paddy was ₹513.73 million in Kharif and ₹501.60 million in Rabi, and the four output indicators are given in Table VII and Fig. 11. Output per cropped area was 47% higher in Rabi (₹2,04,733 per ha against ₹1,39,071 per ha). This agrees with the mandal-level yield estimates in the agricultural records, which were 5,722–6,111 kg/ha in Kharif and 7,033–8,722 kg/ha in Rabi. Per unit of command area, the picture reverses slightly: Kharif was 2.4% higher (₹1,05,740 against ₹1,03,243 per ha) because 76% of the command area was cropped in Kharif but only 50% in Rabi. Output per unit of water consumed was nearly the same in the two seasons (₹25.97 and ₹26.60 per m³), so the two crops convert evapotranspired water into value at a similar rate. Output per unit of irrigation supply rose from ₹0.59 to ₹0.86 per m³, mainly because less water was recorded as supplied in Rabi (580.2 MCM against 865.4 MCM).

TABLE VII AGRICULTURAL OUTPUT INDICATORS

Quantity	Kharif	Rabi
Production value (₹ million)	513.73	501.60
Irrigated cropped area (ha)	3,694	2,450
Command area (ha)	4,858.4	4,858.4
Water consumed, V_{ET} (MCM)	19.78	18.86
Irrigation supply, V_s (MCM)	865.37	580.20
O_c (₹/ha of cropped area)	1,39,071.17	2,04,733.40
O_a (₹/ha of command area)	1,05,739.84	1,03,242.70
O_w (₹/m³ consumed)	25.97	26.60
O_s (₹/m³ supplied)	0.59	0.86

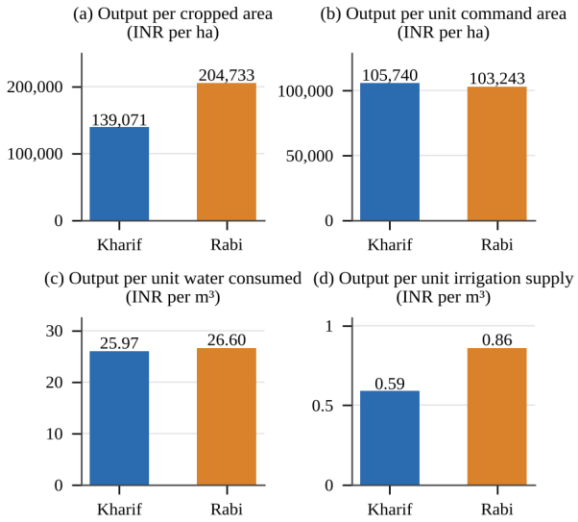


Fig. 11. Output indicators for the Kharif and Rabi seasons: (a) per cropped area, (b) per command area, (c) per unit water consumed, (d) per unit irrigation supply.

F. Supply-to-demand indicators

The recorded irrigation supply was 865.37 MCM (30.56 TMC) in Kharif and 580.20 MCM (20.49 TMC) in Rabi. Compared with the CROPWAT demand, this gives RWS values of 116.64 and 22.35 and RIS values of 186.22 and 31.92 (Table VIII, Fig. 12).

All four values are far above 1, so the recorded supply in both seasons exceeds the estimated requirement. The ratios are five to six times higher in Kharif than in Rabi, in line with the much smaller Kharif irrigation requirement under monsoon rainfall.

TABLE VIII SUPPLY-TO-DEMAND INDICATORS

Quantity	Kharif	Rabi
Irrigation supply (TMC)	30.560	20.490
Crop water demand (TMC)	0.262	0.917
Irrigation requirement (TMC)	0.164	0.642
RWS	116.64	22.35
RIS	186.22	31.92

These magnitudes should not be read as field-level over-irrigation of the paddy. The recorded Kharif supply of 30.56 TMC is many times the project allocation of 1.250 TMC and the 0.423 TMC storage, and the monthly irrigation-outflow entries (up to 4,020 cusecs) exceed the 250 cusecs design discharge of the main canal.

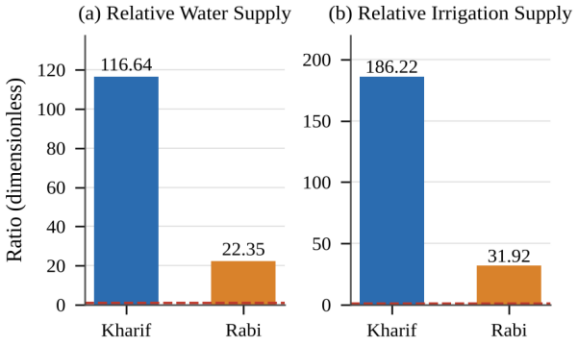


Fig. 12. Supply-to-demand indicators: (a) relative water supply and (b) relative irrigation supply; the dashed line marks a ratio of 1.

This suggests that the monthly records include releases other than canal deliveries, such as monsoon flood passage, or that converting monthly cusec entries to volume overstates the quantity delivered. The ratios therefore indicate chiefly that release records and CROPWAT demand are not yet on a comparable accounting basis. They support the view that canal deliveries should be metered separately from surplus and spill, so that RWS and RIS can be used as dependable adequacy indicators [1], [4]. The seasonal ordering is more robust than the absolute values: the supply is proportionately far more generous in the monsoon season than in the dry season, when the crop depends almost entirely on canal water.

G. Limitations

The findings rest on a single year, a single representative climate station, an uncalibrated rainfall–runoff model and release record whose basis is uncertain, as discussed above. Output indicators use production values for one year and one crop. Multi-year records, field-level discharge measurements and calibration of HEC-HMS would strengthen the assessment. Because delivery adequacy, equity and dependability were not evaluated at outlet level, as in [7] and [8], the indicators describe system-level behaviour only.

VI. CONCLUSIONS

1) The HEC-HMS model of the 114.5 km² Pampa watershed produced a peak discharge of 84.2 m³/s and an annual runoff of 146.49 MCM (5.173 TMC) for 2025, which is 12.23 times the gross storage capacity of the reservoir. Monthly simulated inflow follows the timing of recorded inflow (correlation 0.90) but is 1.68 times larger in total, as expected for an uncalibrated model.
2) CROPWAT showed a strong seasonal contrast. Kharif paddy needed only 68.1 mm of actual irrigation, while Rabi paddy needed 695.7 mm, because effective rainfall fell from 702.0 mm to 70.8 mm. Rabi gross demand was 25.975 MCM against 6.638 MCM in Kharif.
3) Recorded supply exceeded estimated demand in both seasons (RWS 116.64 and 22.35; RIS 186.22 and 31.92). These ratios chiefly reflect the difficulty of separating canal deliveries from other releases and should be revisited with metered canal data.
4) Output per cropped area was higher in Rabi (₹2,04,733 per ha) than in Kharif (₹1,39,071 per ha), and output per unit of water consumed was similar (₹26.60 and ₹25.97 per m³).
5) The approach of linking catchment runoff, storage, crop demand, supply and output offers a workable framework for diagnosing medium irrigation systems. Priorities for the Pampa system are calibrating the hydrological model, metering canal deliveries and scheduling releases according to crop demand and rainfall.

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