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Geospatial Hydrological Modelling and Linear-Programming-Based Optimisation of Water and Land Allocation in a Canal Command Area: A SWAT-Based Case Study of the Purna Irrigation Project, Maharashtra, India

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ABSTRACT

Sustainable management of surface water resources in large canal command areas requires an integrated understanding of catchment hydrology, crop water demand, canal delivery performance and land-water allocation economics. This study presents an integrated assessment of the Purna Irrigation Project (PIP), a major canal irrigation scheme of the Marathwada region of Maharashtra, India, combining the Soil and Water Assessment Tool (SWAT) with hydraulic performance evaluation and a linear-programming (LP) optimisation framework. The catchment (7784 km²) draining to the Siddheswar reservoir was delineated into four sub-basins and fourteen hydrological response units using a 90 m Shuttle Radar Topography Mission (SRTM) digital elevation model, land-use/land-cover classification and soil textural data prepared in ArcGIS. The model was calibrated (1992–2004) and validated (2005–2013) against observed monthly streamflow using the SWAT-CUP SUFI-2 algorithm, achieving a coefficient of determination (R^2) of 0.98 and Nash–Sutcliffe efficiency (NSE) of 0.98 during calibration, and R^2 of 0.95 with NSE of 0.56 during validation, indicating good-to-very-good model performance as per established rating criteria. Average annual water availability in the reservoir over the 1992–2013 simulation period was 927.72 Mm³, of which 540.92 Mm³ (58.3%) was utilised for irrigation, drinking and lift-irrigation purposes. Crop water requirements were estimated for eleven major crops using the FAO-56 Penman–Monteith approach with stage-wise crop coefficients, and canal delivery performance for the Basmat branch canal was evaluated using adequacy, efficiency, equity, dependability, deficiency and wastage indicators, revealing poor-to-fair system performance (mean adequacy = 0.19; mean efficiency = 0.84; mean equity coefficient of variation = 0.89). A linear-programming model with land and water availability constraints was developed to maximise net benefit across seven cropping-intensity scenarios (10–100%). Results indicate that the existing cropping pattern, operating at 53% cropping intensity and consuming approximately 70% of available reservoir water, generated a net benefit of Rs. 210.67 crores from 30,734 ha, whereas full utilisation of the 57,988 ha command area under the optimised scenario (100% cropping intensity) could nearly double net returns to Rs. 416.00 crores. The study demonstrates that an integrated SWAT–performance-indicator–LP framework provides a transferable, data-efficient decision-support tool for water allocation planning in data-scarce semi-arid canal command areas, and recommends reallocation of area under high-water-consuming, low-return perennial crops (sugarcane, banana) toward higher water-productivity field crops (wheat, gram, cotton, turmeric).

Keywords: SWAT model; canal command area; water allocation; linear programming; hydraulic performance indicators; crop water productivity; Purna Irrigation Project

INTRODUCTION

Water is among the most spatially and temporally variable natural resources, and its sustainable management has become one of the defining challenges of contemporary agricultural and economic development. Agriculture remains the dominant consumer of freshwater globally, accounting for roughly 70–71% of total withdrawals, with the share rising to nearly 90% in many developing countries. Since 1970, global water demand across domestic, industrial and agricultural sectors has grown at approximately 2.4% per annum, while per-capita water availability across much of Asia has declined by 40–60% over the latter half of the twentieth century and is projected to fall further in the coming decades. In India, per-capita water availability has declined steadily from 5177 m^3 in 1951 to about 1544 m^3 in 2011, with projections of further decline to 1401 m^3 by 2025 and 1191 m^3 by 2050, driven by population growth, industrialisation, urbanisation and a falling groundwater table.

Within India, the state of Maharashtra and particularly its semi-arid Marathwada region exemplify the acute tension between limited and erratic monsoon-dependent water supply and growing multi-sectoral demand. Marathwada, spanning 64,525 km^2 with an average annual rainfall of only 792 mm distributed across scarcity, assured and moderate rainfall zones, depends critically on irrigation infrastructure for agricultural stability. The Purna Irrigation Project (PIP), constructed on the Purna river — a tributary of the Godavari — is among the major irrigation schemes serving this region, yet like most large Indian canal command areas it suffers a persistent gap between created and utilised irrigation potential, attributable to inadequate hydrological characterisation, unlined conveyance infrastructure, inequitable water distribution and the absence of a systematic, spatially explicit water allocation framework.

Conventional approaches to irrigation water management in such systems have historically relied on rule-of-thumb canal operation schedules and aggregated water balance estimates that do not capture the spatial heterogeneity of soils, land use, cropping pattern and topography within a catchment or command area. The integration of Geographic Information Systems (GIS) with physically based, semi-distributed hydrological models has substantially improved the capacity to represent this heterogeneity. Among such tools, the Soil and Water Assessment Tool (SWAT), developed by the United States Department of Agriculture–Agricultural Research Service, has emerged as one of the most widely validated river-basin and watershed-scale models worldwide, owing to its capacity to simulate the spatial and temporal dynamics of runoff, evapotranspiration, percolation and reservoir storage using readily available digital elevation, land-use and soil datasets.

Beyond hydrological assessment, the equitable and efficient delivery of available water to the command area is governed by the operational performance of the canal distribution network. Performance indicators such as adequacy, efficiency, equity, dependability, deficiency and wastage, first formalised by Molden and Gates (1990), provide a standardised quantitative basis for diagnosing where and when a canal system under- or over-delivers water relative to crop requirement. Coupling such diagnostics with an optimisation framework — typically linear programming (LP) — allows water and land resources to be allocated across competing crops so as to maximise economic returns subject to physical and agronomic constraints, an approach with a long history in irrigation planning research but one that has been comparatively under-applied to medium-sized, data-constrained Indian canal commands such as PIP.

Despite the demonstrated utility of SWAT-based water resource assessment and LP-based allocation planning individually, few published studies have combined catchment-scale hydrological simulation, command-area canal performance evaluation and crop-water-productivity-based optimisation within a single, internally consistent analytical framework calibrated against long-term observed data for a Marathwada-region irrigation project. This gap is significant because water allocation decisions made on the basis of hydrological assessment alone, without consideration of canal delivery performance and the economic trade-offs among competing crops, risk perpetuating the very inefficiencies such interventions are intended to resolve.

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The present study addresses this gap through an integrated investigation of the Purna Irrigation Project with the following specific objectives: (i) to assess surface water availability in the Purna reservoir catchment using the SWAT model calibrated and validated against thirty-five years of observed streamflow and reservoir storage data; (ii) to characterise the existing land use, soil properties and cropping pattern of the canal command area using GIS-based spatial analysis; (iii) to estimate irrigation water demand for major crops under the existing rotational water-supply regime using the FAO-56 Penman–Monteith approach and stage-wise crop coefficients, and to evaluate canal delivery performance using standard hydraulic performance indicators; and (iv) to develop and solve a linear-programming model under a range of land- and water-availability constraints in order to identify an economically optimum cropping pattern that maximises net benefit to farmers in the command area.

MATERIALS AND METHODS

Description of the Study Area

The Purna Irrigation Project is located in the Marathwada region of Maharashtra State, India, between 17°35′ N and 20°40′ N latitude and 74°40′ E and 78°15′ E longitude. The project comprises two storage structures on the Purna river, a tributary of the Godavari: the Yeldari reservoir, located near Yeldari village in Jintur taluka of Parbhani district, and the downstream Siddheswar diversion/storage reservoir located approximately 64 km downstream near Siddheswar village in Aundha taluka of Hingoli district. First conceived in 1921 and constructed between 1958 and 1968, PIP was designed with a planned command area of approximately 64,000 ha and presently benefits 232 villages across the Parbhani, Hingoli and Nanded districts, with an established irrigation potential of 57,988 ha. The catchment area draining to the Siddheswar reservoir outlet, which forms the hydrological domain of the present study, covers 7784 km² and lies within the arid (monsoon) agro-climatic zone of Marathwada, characterised by warm, wet summers (June–September monsoon) and dry, cold winters.

Data Sources and Geospatial Database Development

A multi-source geospatial and tabular database was assembled to support hydrological modelling and command-area analysis. Two Shuttle Radar Topography Mission (SRTM) tiles (SRTM_52_08 and SRTM_52_09) with 90 m × 90 m spatial resolution were obtained from the NASA SRTM data portal and mosaicked to generate a digital elevation model (DEM) of the study area in ERDAS Imagine software. Survey of India toposheets at 1:50,000 scale (Ajanta, Aurangabad, Buldhana, Parbhani and Nanded sheets) obtained from the Regional Remote Sensing Centre, Nagpur, together with Cartosat and LISS-IV merged satellite imagery, were used to verify and correct the digitised catchment boundary, drainage network, settlements, water bodies and canal network. Land-use/land-cover (LULC) classification and a soil textural map required as SWAT inputs were prepared in the ArcGIS environment. Daily meteorological records (maximum and minimum temperature, relative humidity, wind speed, bright sunshine hours and precipitation) for the period 1979–2013 were obtained from five neighbouring weather stations and from the Global Weather Data generator hosted on the SWAT website. Daily reservoir gauge levels, canal network details, daily canal water release records and year-wise cropping-pattern data for the command area were obtained from the office of the Executive Engineer, Purna Irrigation Division, Basmat. All non-spatial datasets relating to climate, soil, crop, drainage network, groundwater, reservoir operation and management practices were organised in a relational database (MS Access) prior to import into the SWAT modelling environment.

SWAT Model Configuration

The catchment area of the Purna (Siddheswar) reservoir was delineated and divided into four sub-basins using the ArcSWAT interface, within which fourteen hydrological response units (HRUs) were generated by overlaying the LULC map, soil map and slope map with user-defined threshold values to balance computational tractability against spatial representativeness. For the downstream canal command area, an analogous delineation using predefined watershed and canal-network shapefiles (in polygon and polyline format respectively, with associated attribute tables) generated sixty-seven allocation units (AUs) within twelve sub-basins, combining soil, land-utilisation and slope categories. The model computes the daily soil water balance for each HRU/AU using the curve-number method for surface runoff estimation and routes the resulting water yield — the sum of surface runoff, lateral flow and groundwater contribution, net of transmission and reservoir losses — through the stream network to the catchment outlet. Reservoir routing employed the target-release (IRESCO) simulation option within SWAT to represent the controlled outflow regime of the Siddheswar reservoir. Crop growth was simulated using the embedded EPIC plant-growth sub-model with a potential-heat-unit scheduling approach.

Sensitivity Analysis, Calibration and Validation

Given the substantial number of parameters governing SWAT outputs, a global sensitivity analysis was first conducted using the Latin Hypercube one-factor-at-a-time (LH-OAT) sampling procedure implemented in SWAT-CUP, in order to identify the parameters exerting the strongest influence on simulated streamflow prior to calibration. Four parameters — the SCS curve number (CN2), baseflow alpha factor (ALPHA_BF), groundwater delay (GW_DELAY) and threshold water depth for return flow (GWQMN) — were identified as most sensitive and were subsequently adjusted during calibration.

Calibration and validation were performed at a monthly time step using the Sequential Uncertainty Fitting (SUFI-2) algorithm within SWAT-CUP, developed by Eawag, the Swiss Federal Institute of Aquatic Science and Technology. The thirty-five-year simulation period (1979–2013) was preceded by an eight-year warm-up period (1984–1991) to stabilise initial soil-moisture and groundwater storage conditions. The subsequent thirty-year period (1992–2013) was split following the split-sample approach into a thirteen-year calibration period (1992–2004) and a nine-year validation period (2005–2013), using observed monthly streamflow and reservoir storage-volume data recorded at the Siddheswar outlet gauging station. In SUFI-2, parameter and input uncertainty are propagated to model output as the 95% prediction uncertainty (95PPU) band, characterised by the p-factor (the percentage of observed data bracketed within the 95PPU) and the r-factor (the relative width of the uncertainty band); an ideal calibration approaches a p-factor of unity and an r-factor of zero.

Model performance was quantified using a combination of standard regression statistics, dimensionless indices and error-based measures, following the guidelines of Moriasi et al. (2007): the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS) and the RMSE-observations standard deviation ratio (RSR). Model performance is generally considered satisfactory for monthly streamflow simulation when $R^2 \geq 0.65$, NSE ≥ 0.50, PBIAS lies within ±25% and RSR ≤ 0.70.

Estimation of Crop Water Requirement

Reference evapotranspiration (ET_0) was computed within SWAT using the FAO-56 Penman–Monteith method, driven by the 35-year daily weather record. Stage-wise crop coefficients (Kc) were independently developed following standard FAO-56 procedures for the eleven major crops cultivated in the command area — wheat, Rabi sorghum, gram, sunflower, cotton, turmeric, groundnut, forage, sugarcane, banana and sweet orange — and were used to compute crop evapotranspiration ($ETc = Kc \times ET_0$) for each crop growth stage. Effective rainfall was estimated using the USDA Soil Conservation Service (SCS) method, and net crop water requirement was obtained as the difference between ETc and effective rainfall. Total irrigation water requirement at each canal outlet (QR) was computed from the net irrigation requirement, the area irrigated under each outlet, and an assumed overall (conveyance plus application) irrigation efficiency of 40%, consistent with field observations for unlined canal systems of this type.

Hydraulic and Agricultural Performance Evaluation

Canal delivery performance was assessed for the Basmat branch canal (Limbgaon sub-division) of PIP — selected as a representative case study owing to availability of complete rotation-wise water-release records for thirty-five outlets (R = 35) over nine months of canal operation (T = 9, irrigation seasons excluding the July–September monsoon closure) for the year 2013–14 — using the hydraulic performance indicators of Molden and Gates (1990), computed with the SPI_CANAL software of Raut and Khodke (2007). For a region or sub-region R served by the system over period T, with QD the volume of water delivered and QR the corresponding volumetric requirement in time interval t:

Adequacy (PA) is computed as the temporal and spatial average of $pA = QD/QR$ (where $QD \leq QR$), or unity otherwise, and expresses the system's ability to meet required delivery. Efficiency (PF) is the average of $pF = QR/QD$ (where $QR \leq QD$), or unity otherwise, and reflects the system's ability to avoid over-delivery relative to requirement. Dependability is expressed through the temporal coefficient of variation (CVT) of QD/QR over the period T, while equity is expressed through the spatial coefficient of variation (CVR) of QD/QR across outlets, with values closer to zero indicating greater uniformity of delivery. Deficiency (PDF) is computed as the average of $(QR - QD)/QR$ where $QR > QD$, and wastage (PW) as the average of $(QD - QR)/QR$ where $QD > QR$. Agricultural performance was further characterised through irrigation intensity (ratio of irrigated area to command area), cropping intensity (ratio of total cropped area to command area), standardised gross value of production (SGVP), and crop water productivity (CWP), computed as the ratio of crop yield (q ha^{-1}) to seasonal crop evapotranspiration expressed on a volumetric basis (m^3 ha^{-1}), following the methodology of Molden et al. (2003).

Linear-Programming Optimisation of Land and Water Allocation

A linear-programming (LP) model was formulated to identify the crop area allocation that maximises net economic benefit from the command area, subject to land- and water-availability constraints, following the general matrix formulation of Maji and Heady (1980). The objective function maximises $Z = \Sigma B_j \cdot A_j$, where Bj is the net benefit per hectare from the j^{th} crop (computed from minimum support price, yield and cost of cultivation) and A_j is the area allocated to crop j. The model is subject to (i) reservoir capacity constraints (storage at any month bounded between dead storage and maximum capacity), (ii) monthly water-requirement constraints (water released for irrigation must meet or exceed aggregate crop water requirement in that month), (iii) reservoir continuity constraints linking storage, inflow, release, evaporation and percolation losses (assumed as 15% of average monthly storage, following Loucks et al., 1981) across successive months, and (iv) land-availability constraints (the sum of area under all crops must not exceed total available command area). The LP problem was solved using the simplex method under seven discrete scenarios of cropping intensity and corresponding water availability — 10%, 30%, 50%, 60%, 70%, 80% and 100% — in addition to the existing (53% cropping intensity) cropping pattern observed for the 2013–14 reference year, enabling direct comparison of net returns, water requirement and water utilisation efficiency across the full feasible range of command-area development.

RESULTS AND DISCUSSION

Catchment Characteristics, Land Use and Soil Properties

Analysis of the 35-year (1979–2013) daily weather record indicates a long-term average annual rainfall of 887.6 mm for the Purna catchment, ranging from 611 mm in valley locations to 1406 mm on the surrounding plateau, with no statistically discernible long-term increasing or decreasing trend. Years of notably high rainfall (1983, 1988, 1989, 1990 and 1998) alternated with markedly deficient years (1980, 1982, 1985, 2004, 2007, 2009 and 2011), underscoring the high inter-annual variability characteristic of the semi-arid Marathwada climate. Actual evapotranspiration in the catchment, as simulated by SWAT, varied between 700 and 900 mm per year, equivalent to approximately 36.2% of mean annual precipitation, with average pan evaporation ranging from 3.36 to 4.80 mm day^{-1}.

Land use/land cover analysis of the 90,525.57 ha command area (Fig. 7a) showed that agricultural land occupies the dominant share at 57,988.04 ha (64.06%), followed by pasture land (19,471.53 ha, 21.51%), water bodies (4767.16 ha, 5.27%) and other categories including waste and grazing land (9.16%) that present opportunities for future horticultural development. Soil textural analysis (Fig. 7b) identified sandy clay loam (24.79%) and sandy clay (23.96%) as the dominant textural classes, with basic infiltration rates ranging from 14.3 to 35.9 mm hr^{-1} and soil organic carbon content between 0.28% and 1.26%. Approximately 15% of examined soil profiles were classified as alkaline (pH > 8.6), while the majority of soils were assessed as non-saline. Land irrigability classification placed Class II soils (most suitable for irrigated agriculture) as dominant, covering 23,536.65 ha (26%), followed by Class VI (20,820.88 ha, 23%) and Class III (18,105.11 ha, 20%); the majority of the command area (58.83%) exhibited gentle slopes of 0.0–0.5%, favourable for surface irrigation.

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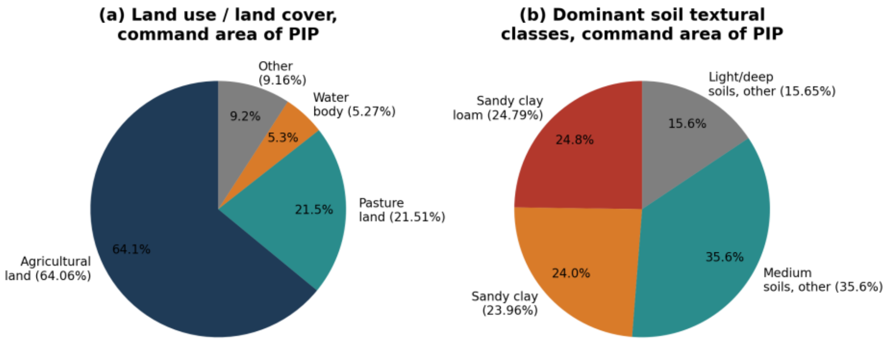

Fig. 1. Land use/land cover (a) and dominant soil textural classes (b) of the Purna Irrigation Project command area.

Sensitivity Analysis, Calibration and Validation of SWAT

Sensitivity analysis using the LH-OAT procedure within SWAT-CUP confirmed the curve number (CN2), baseflow alpha factor (ALPHA_BF), groundwater delay (GW_DELAY) and threshold water depth for return flow (GWQMN) as the four parameters exerting the greatest influence on simulated monthly streamflow, consistent with the dominance of curve-number-driven surface runoff generation in this monsoon-fed catchment. These parameters were subsequently used for model calibration via the SUFI-2 algorithm.

The integrated SWAT–performance-evaluation–LP optimisation framework adopted in this study is summarised schematically in Fig. 2.

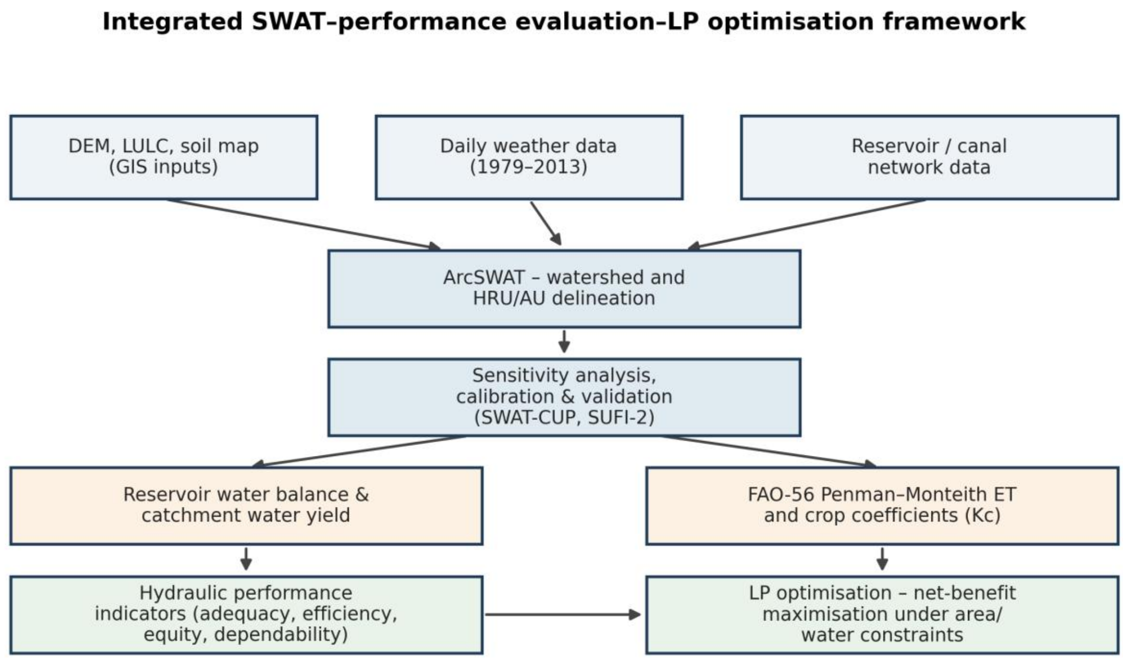

Fig. 2. Integrated SWAT–canal performance evaluation–linear programming optimisation framework adopted in the present study.

Comparison of monthly observed and SWAT-simulated streamflow at the Siddheswar outlet during the calibration period (1992–2004) showed close visual agreement in both timing and magnitude of monsoon-season peaks and dry-season recession (Fig. 3), with a strong linear relationship between observed and simulated values (R^2 = 0.98; Fig. 4).

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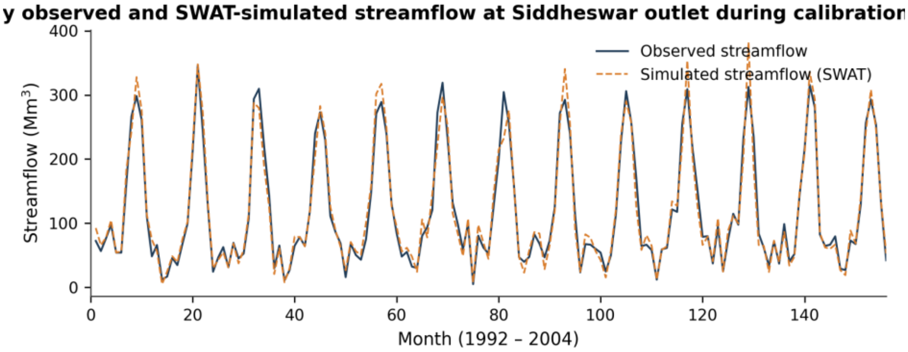

Fig. 3. Monthly observed and SWAT-simulated streamflow at the Siddheswar outlet during the calibration period (1992–2004).

Fig. 4. Scatter plot of observed versus SWAT-simulated monthly streamflow during calibration, with 1:1 reference line and linear regression.

Quantitative performance statistics (Table 1) confirm very good model performance during calibration (RSR = 0.15, NSE = 0.98, PBIAS = −6.7%, R^2 = 0.98) and good performance during validation (RSR = 1.00, NSE = 0.56, PBIAS = −41.9%, R^2 = 0.95), with all calibration-period indices exceeding the satisfactory thresholds specified by Moriasi et al. (2007). The negative PBIAS values recorded during calibration and validation indicate a tendency of the model toward slight overestimation of streamflow in those periods, while the positive PBIAS (18.37%) for the full 1992–2013 simulation period indicates a compensating underestimation tendency when high-rainfall years are included, attributable to the target-release reservoir simulation option used to represent the controlled outflow regime of the Siddheswar reservoir under limited gauge data.

Table 1. SWAT model performance statistics for monthly streamflow simulation at the Siddheswar outlet.

Data set	Period	RSR	NSE	R^2
Calibration	1992–2004	0.15	0.98	0.98
Validation	2005–2013	1.00	0.56	0.95

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Data set	Period	RSR	NSE	R^2
Full simulation period	1992–2013	1.44	−1.08	0.97

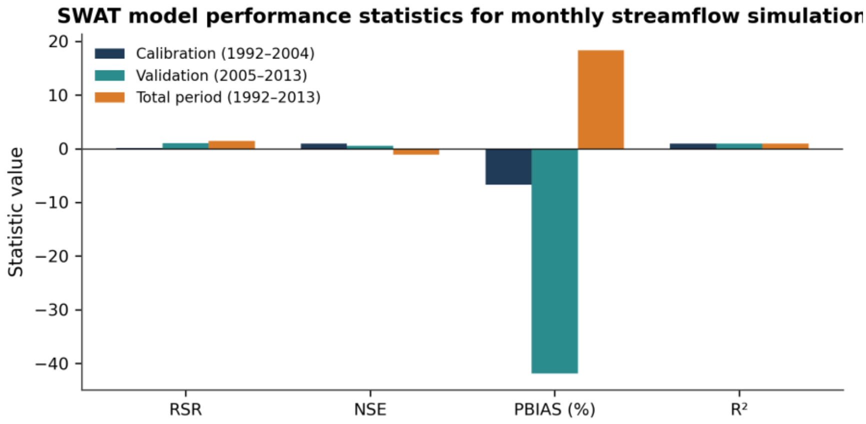

Fig. 5. Comparison of SWAT performance statistics (RSR, NSE, PBIAS, R^2) for monthly streamflow across the calibration, validation and full simulation periods.

These results corroborate prior applications of SWAT in Indian semi-arid catchments and demonstrate that, despite the absence of upstream hydrometric stations and reliance on a single outlet gauge for calibration, the model adequately reproduces the dominant hydrological behaviour of the Purna catchment for the purposes of water-availability assessment.

Reservoir Water Availability and Water Balance

Over the 1992–2013 simulation period, the average annual water available in the Siddheswar reservoir was estimated at 927.72 Mm^3, of which 540.92 Mm^3 (58.3% of total availability) was utilised across irrigation, drinking-water supply and lift-irrigation purposes — 351.15 Mm^3 (37.85% of total availability) for canal irrigation, 29.41 Mm^3 (3.17%) for drinking-water supply and 19.07 Mm^3 (2.05%) for lift irrigation — with the remaining 386.12 Mm^3 retained as end-of-season carry-over storage. The average percentage of live storage maintained in the reservoir over the 45-year operational record was 64.27% of maximum live storage capacity, reflecting generally conservative reservoir operation but also indicating periods of substantial under-utilisation of available storage capacity relative to downstream demand.

Sugarcane and banana, the principal perennial crops in the command area, recorded the highest seasonal reference crop evapotranspiration among all cultivated crops, at 2477.17 mm and 2579.33 mm respectively, with corresponding seasonal water requirements of approximately 230.44 Mm^3 for sugarcane alone — a finding with direct implications for the cropping-pattern optimisation discussed in Section 3.5.

Canal Delivery Performance Evaluation

Crop-wise area irrigated under the Basmat branch canal command during 2013–14 was dominated by sugarcane (2870.2 ha, perennial), wheat (2821.4 ha, Rabi) and groundnut (2646.9 ha, hot-weather season), with smaller contributions from forage, Rabi sorghum, turmeric, cotton, gram, sweet orange and banana. Outlet-wise analysis across the thirty-five outlets of the branch canal revealed substantial spatial variability in both irrigated area and the ratio of water utilised to water required: the largest irrigated area (1540.1 ha) was served by the Jangamwadi distributary lift outlet, with a comparatively low utilisation-to-requirement ratio (4.20 Mm^3 utilised against 20.23 Mm^3 required), while the smallest command (19.97 ha, Maralak minor) showed a similarly constrained utilisation ratio (0.80 Mm^3 against 5.48 Mm^3 required). A consistent deficit in water supplied relative to requirement was observed at every outlet, ranging from 11.78% (direct outlets of Basmat distributary) to 95.14% (Babhulgaon minor).

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Temporal evaluation of hydraulic performance indicators across the irrigation year (Fig. 6, Table 2) revealed an average adequacy (PA) of 0.19, ranging from 0.13 to 0.26 across months — well below the threshold of 0.80 generally associated with satisfactory performance — indicating that, on average, the canal system delivered substantially less water than the corresponding crop requirement throughout the year. Efficiency (PF), in contrast, averaged 0.84 (range 0.62–0.95), classified as fair-to-good performance, with the highest monthly efficiency recorded in July (95%), June (91%) and May (89%), indicating that when water was released, it was generally well matched to or in moderate excess of requirement rather than substantially over-supplied. Equity, expressed as the spatial coefficient of variation (CVR) of relative delivery across outlets, averaged 0.89 (range 1.00–1.93 across the available monthly data), denoting poor spatial uniformity of delivery and corroborating field reports of disparities between head- and tail-reach farmers within the command. Dependability (CVT), the temporal coefficient of variation, averaged within the range of 0.97 to 1.52 across months, also indicating inconsistent month-to-month reliability of supply.

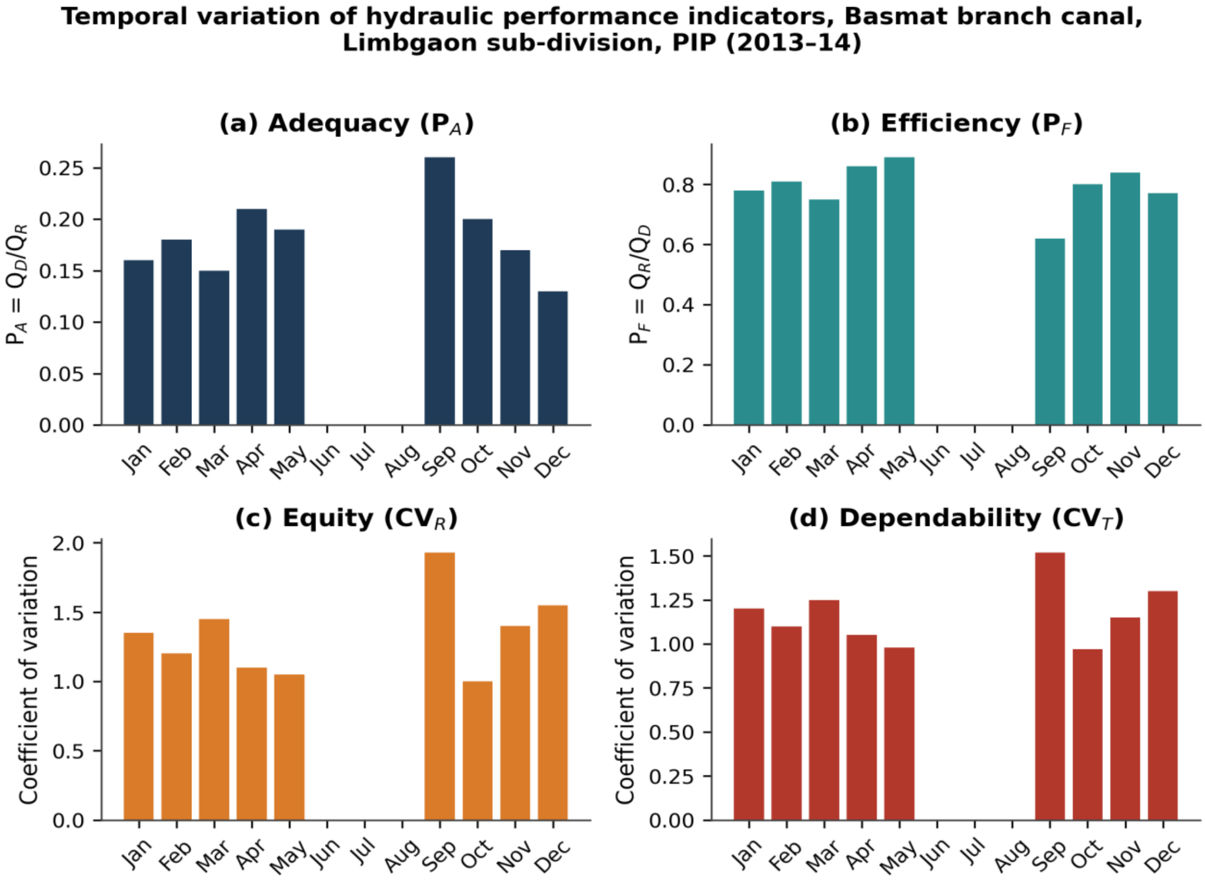

Fig. 6. Temporal variation of (a) adequacy, (b) efficiency, (c) equity and (d) dependability indicators for the Basmat branch canal, Limbgaon sub-division of PIP, 2013–14.

Table 2. Mean hydraulic performance indices for the Basmat branch canal, Limbgaon sub-division, PIP (irrigation year 2013–14).

Performance indicator	Mean value	Performance class
Adequacy (PA)	0.19	Poor
Efficiency (PF)	0.84	Fair to good
Equity (CVR)	0.89	Poor
Dependability (CVT)	1.18*	Poor to fair

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*Mean of monthly CVT values reported in the irrigation-season record.

The combination of poor adequacy and equity but fair efficiency suggests that the Basmat branch canal system's principal performance constraint is insufficient total volumetric release relative to aggregate demand — consistent with the largely unlined conveyance network identified in field inspection — rather than gross mismanagement of the water that is in fact released. This diagnosis is consistent with prior performance evaluations of major Indian canal commands (Molden and Gates, 1990; Molden et al., 1998) that similarly identify conveyance losses and inequitable head–tail distribution as the dominant constraints on system performance in unlined, gravity-fed canal networks.

Linear-Programming-Based Optimisation of Land and Water Allocation

Comparison of canal water availability against aggregate crop water requirement across the seven cropping-intensity scenarios confirmed that crop water requirement exceeded available water in every scenario evaluated, indicating that the command area operates under a structural water deficit irrespective of the level of cropping intensification pursued. At the most conservative scenario (10% cropping intensity), water availability during winter and summer seasons was 24.61 Mm^3 and 64.48 Mm^3 respectively, against requirements of 36.94 Mm^3 and 75.77 Mm^3 — deficits of 33.39% and 9.63%. The deficit widened substantially at higher cropping intensities: under the existing cropping pattern (53% cropping intensity), winter and summer deficits reached 66.09% and 54.01% respectively, the highest of all scenarios evaluated, with the 70% cropping-intensity scenario showing somewhat lower deficits of 55.19% (winter) and 39.42% (summer).

Despite this structural deficit, the linear-programming model identified substantial scope to increase net economic benefit through reallocation of land and water among crops of differing water productivity. Under the existing (2013–14) cropping pattern — 30,734 ha cultivated at 53% cropping intensity, utilising approximately 70% of available reservoir water — the LP model computed a total net benefit of Rs. 210.67 crores (Table 3), with benefit–cost ratios of 2.68 for wheat, 2.63 for gram, 2.60 for Rabi sorghum and 2.77 for turmeric, contrasted with markedly lower returns for the high-water-consuming perennial crops sugarcane (B:C = 1.39) and sweet orange (B:C = 1.51), and an intermediate value for banana (B:C = 2.24).

Table 3. Net benefit and benefit–cost ratio by crop under the existing (53% cropping intensity) cropping pattern, canal command area of PIP.

Crop	Yield (q ha^{-1})	Net benefit (Rs. lakh ha^{-1})	Net benefit (Rs. crores)	B:C ratio
Wheat	19.14	0.16	20.51	2.68
Rabi sorghum	10.10	0.10	5.36	2.60
Gram	7.44	0.11	1.56	2.63
Sunflower	7.46	0.11	1.06	2.61
Cotton	13.61	0.28	8.79	2.54
Turmeric	21.37*	2.77	30.70	2.23
Groundnut	10.92	0.11	11.10	1.31
Forage	84.35*	0.34	12.49	2.71
Sugarcane	77.98*	0.89	57.92	1.39
Banana	138.10*	9.74	46.02	2.24

Sweet orange	30.02*	2.85	15.15	1.51
Total	—	8.62 (mean)	210.67	—

*Yield expressed as metric tonnes per hectare (MT ha^{-1}).

Across the seven LP-optimised cropping-intensity scenarios (Table 4, Fig. 7), total net returns increased monotonically with both cropping intensity and water allocation, from Rs. 41.60 crores at the most conservative 10% cropping-intensity scenario (5799 ha cropped, 93.08 Mm^3 water released) to a maximum of Rs. 416.00 crores at full (100%) cropping intensity (57,988 ha cropped, 891.04 Mm^3 water released). Notably, Scenario III (50% cropping intensity, Rs. 208.00 crores from 28,994 ha) achieved a total net return only marginally below that of the existing cropping pattern (Rs. 210.67 crores from 30,734 ha) despite cultivating 1740 ha less area, implying a modest efficiency gain available through more rational crop-area allocation even without intensifying overall cultivation.

Table 4. LP-optimised cropped area, water requirement, water released and total net returns under seven cropping-intensity and water-availability scenarios, canal command area of PIP.

Scenario	Cropping intensity (%)	Cropped area (ha)	Water required (Mm^3)	Water released (Mm^3)	Net return (Rs. crores)
Existing	53	30,734	1127.41	473.87	210.67
I	10	5,799	112.71	93.08	41.60
II	30	17,396	338.17	270.78	124.80
III	50	28,994	563.69	449.26	208.00
IV	60	34,793	676.31	537.33	249.60
V	70	40,592	1127.41	624.71	291.20
VI	80	46,390	901.77	717.57	332.80
VII	100	57,988	1127.41	891.04	416.00

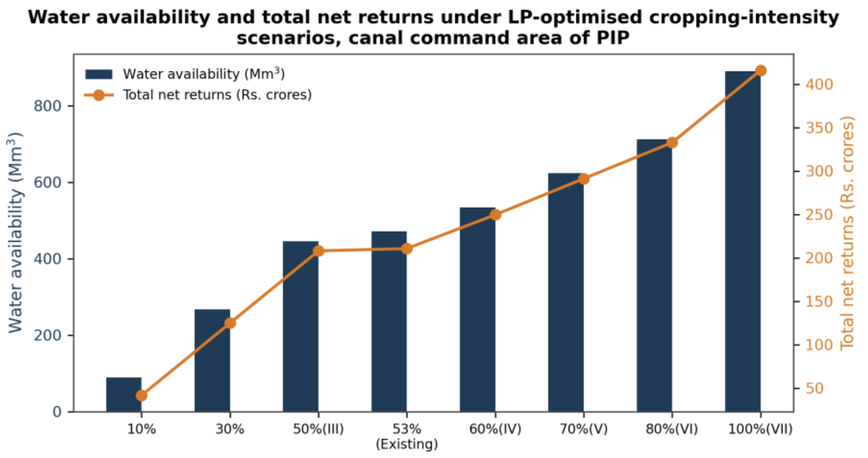

Fig. 7. Water availability and total net returns under LP-optimised cropping-intensity scenarios for the canal command area of PIP.

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Examination of crop-wise area reallocation between the existing pattern and the optimised 100% cropping-intensity scenario (Fig. 8) shows proportional expansion across all crops broadly in line with the overall 1.89-fold increase in total cropped area, rather than a disproportionate shift toward any single high-return crop, since the LP land-availability constraint (Eq. 3.151 of the underlying model) bounds total area while the objective function favours, at the margin, crops with the highest net benefit per unit of water consumed. Wheat area increased from 9456 ha to 14,630 ha, cotton from 2270 ha to 8078 ha and groundnut from 5632 ha to 11,476 ha, while sugarcane — despite its high gross return per hectare — increased proportionally less (3798 ha to 4801 ha) owing to its comparatively low net benefit per unit of water consumed (B:C = 1.39) relative to field crops such as wheat, gram and cotton.

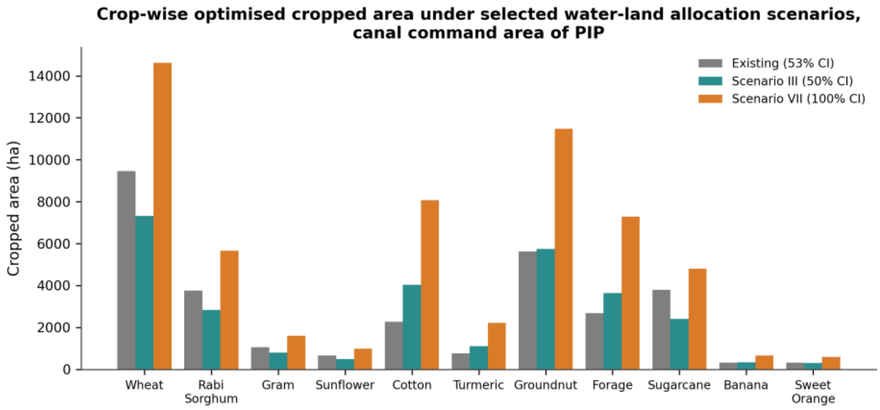

Fig. 8. Crop-wise optimised cropped area under the existing cropping pattern, Scenario III (50% cropping intensity) and Scenario VII (100% cropping intensity), canal command area of PIP.

Under the recommended full-utilisation (Scenario VII) allocation, the optimum cropping pattern comprises 22,865 ha under Rabi-season crops, 10,299 ha under two-seasonal crops (cotton and turmeric), 18,765 ha under hot-weather-season crops, and 6,060 ha under perennial and horticultural crops, yielding the maximum attainable net benefit of Rs. 416.00 crores from the available water resource. These results collectively indicate that, given the structural water deficit confirmed in Section 3.5, the most economically rational management strategy for PIP combines a moderate reduction in the proportion of command area devoted to high-water-consuming, comparatively low-water-productivity perennial crops (sugarcane, banana) with reallocation of the released water and land toward field crops exhibiting both lower seasonal water requirement and higher benefit–cost ratios, namely wheat, gram, cotton and turmeric — a conclusion that aligns with established principles of deficit-irrigation-based water productivity optimisation in semi-arid canal commands (Doorenbos and Kassam, 1979; Molden et al., 2003) and with similar LP-based water-allocation studies reported for other Indian and international canal systems.

Implications for Irrigation Water Management Policy

The integrated findings of this study carry several implications for the operational management of PIP and, by extension, comparable medium-sized canal commands in semi-arid India. First, the consistently poor adequacy and equity scores recorded for the Basmat branch canal, contrasted with fair efficiency, point toward conveyance-stage interventions — principally canal lining to reduce transmission losses and revised rotational scheduling to improve head–tail equity — as a higher-priority near-term investment than further on-farm efficiency measures. Second, the LP optimisation results demonstrate that net economic benefit to the command area can be increased substantially, even without additional water resource development, through a combination of (a) extending the cultivated area toward the full irrigable command of 57,988 ha where water permits, and (b) progressively substituting area under sugarcane and banana — crops that combine high absolute water demand with comparatively low water productivity in this command — with field crops of higher benefit–cost ratio. Third, the persistence of a water deficit across every scenario evaluated, including the most conservative 10% cropping-intensity case, underscores those reallocation gains alone cannot resolve PIP's structural water scarcity; complementary measures such as deficit-irrigation scheduling during drought-sensitive growth stages, water-

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pricing reform to internalise scarcity value, and strengthening of Water Users' Associations to improve distributional equity will be necessary alongside the cropping-pattern reallocation recommended here.

CONCLUSION

This study demonstrates the value of an integrated SWAT–canal performance evaluation–linear programming framework for diagnosing and addressing water allocation inefficiencies in a medium-sized semi-arid canal command area with limited hydrometric instrumentation. The SWAT model, calibrated and validated against thirty-five outlets of observed monthly streamflow and reservoir storage data spanning 1992–2013, reproduced catchment hydrology with very good accuracy during calibration (NSE = 0.98, R^2 = 0.98) and good accuracy during validation (NSE = 0.56, R^2 = 0.95), confirming the model's suitability for water-availability assessment in the Purna catchment despite the absence of upstream gauging stations. Average annual reservoir water availability of 927.72 Mm^3 over the study period, of which only 58.3% was utilised across all sectors, juxtaposed against persistently poor canal-delivery adequacy (mean PA = 0.19) and equity (mean CVR = 0.89) for the Basmat branch canal, identifies conveyance-stage losses and inequitable distribution — rather than absolute water scarcity at the reservoir scale — as a principal constraint on realised irrigation benefit. The linear-programming optimisation further establishes that net economic returns to the command area could increase from Rs. 210.67 crores under the existing 53% cropping-intensity pattern to Rs. 416.00 crores under full utilisation of the 57,988 ha irrigable command, primarily through proportional reallocation of land toward field crops of higher water productivity (wheat, gram, cotton, turmeric) and away from the comparatively low-benefit–cost-ratio perennial crops sugarcane and banana. Because every cropping-intensity scenario evaluated, including the most conservative, exhibited a structural seasonal water deficit, the study concludes that cropping-pattern optimisation should be pursued in conjunction with, rather than as a substitute for, conveyance infrastructure improvement and demand-management measures. The methodological framework developed here — combining freely available remote-sensing-derived geospatial inputs, a physically based semi-distributed hydrological model, standardised hydraulic performance indicators and a tractable LP optimisation — is readily transferable to other data-constrained canal command areas across the Marathwada region and comparable semi-arid irrigation systems in the Indian subcontinent.

Limitations and Future Research

The present analysis relies on streamflow and storage data from a single outlet gauging station, in the absence of upstream hydrometric stations within the catchment, which constrains the spatial resolution at which model calibration can be independently verified. The hydraulic performance evaluation was similarly confined to the Basmat branch canal owing to data availability, and extension of rotation-wise water-release monitoring to the remaining sub-divisions of PIP would permit a more complete command-area-wide performance assessment. The LP optimisation framework, while capturing the principal land, water and continuity constraints, assumes homogeneous soil and management conditions across the command area and does not explicitly incorporate inter-annual climate variability or groundwater conjunctive-use opportunities; future work could usefully couple the present framework with a stochastic or multi-year dynamic optimisation approach and with groundwater-surface water conjunctive allocation models to further refine recommended cropping strategies under climate variability.

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Competing Interests

The author has declared that no competing interests exist.

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