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Optimal Operation of Multipurpose Reservoir

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Abstract

A Linear Programming Model (LP) and Particle Swarm Optimization Model have been proposed for utilizing surface water resources to achieve the optimal operation policy of a multipurpose single reservoir. Maximization of releases for irrigation, hydropower and water supply is taken as an objective function to optimize the objective through Particle Swarm Optimization techniques and Optimization Tool. The objective function is subjected to constraint bounds like irrigation demand, Reservoir storage capacity, canal capacity, Turbine Capacity, and hydrological continuity. The proposed model is applied to a case study of Bhatsa Reservoir at Shahapur, Thane, Maharashtra, India. The proposed model is initially optimized using Optimization Tool, i.e., Lingo, which results in the maximization of releases for irrigation of 108.09 Mm^3 and releases for hydropower of 180 Mm^3. Moreover, the same problem has been solved using the Particle Swarm Optimization (PSO) technique using MATLAB. Parameters used in PSO include: Population Size = 75, Number of Variables = 12, No of Iterations = 50, Maximum and Minimum of Irrigation Weight = 0.9 & 4, respectively. Acceleration factors C1 and C2 = 1 & 2 respectively. The maximized water releases for irrigation storage are 101.3. Mm^3 and for hydropower storage are 180 Mm^3. PSO solutions are compared with those of Linear Programming, and results are quite similar. Thus, PSO can be considered a suitable optimization technique for multi-objective reservoir management. LP model and PSO have both produced optimal releases for irrigation and hydropower storage in the reservoir at the end of each month, along with the head over the turbine.

Keywords: Optimization: Reservoir operation: Linear programming: Inflow: Particle swarm optimization.

Introduction

Because of the consequences of climate change, there is tempo- spatial variability of rainfall, which causes uncertainties in inflow, continuously increasing water demand for domestic use, irrigation and hydropower generation; therefore, management of water resources is becoming a complex task nowadays. Reservoirs are artificial storage facilities built across rivers to store a large volume of water, which can be used throughout the year to fulfil every request. With the large amount of water stored in the area, the losses may occur in the form of several different losses, such as evaporation, percolation, and others. Therefore, designing effective policies for the water supply, taking into consideration all the factors affecting it, becomes essential. The amount of storage in the reservoir changes with the passage of each month owing to the monsoon season; there will be a change in the water requirement and supply every month. The Standard Operating Policy (SOP) is one of the simplest and most commonly used operating policies in reservoirs, whereby the release of water depends on the best possible demand according to the availability of water. With the rise in the population and rapid urbanization, there may always be a need for releasing water only for domestic use, resulting in the risk of water deficit for future irrigation and hydropower requirements.

Multi-objective reservoir operation models contain several complexities such as nonlinear functional relationships, more decision variables, physical, technical and operational constraints. As a result, there are numerous efforts made by several researchers using various methods to reduce the deficit. If multi-objective operation models contain a linear relationship between objective functions and variables, then a linear programming model can be used to find solutions. However, when the models contain non-linearity, recently, the metaheuristic algorithms like genetic algorithm (GA), PSO, etc. have been used to address the issue of water resources optimization. The application of the above-mentioned meta-heuristic algorithms for solving reservoir operation problems is illustrated as follows. Therefore, this investigation aims to maximize the monthly releases using linear programming and PSO techniques for a single multipurpose reservoir. The discharges from the reservoir depend on the operating policies, i.e., the rule curves adopted. The rule curve serves as a store which indicates the level of water that should be maintained to satisfy the demand.

Jothiprakash and Arunkumar (2012) utilized optimization technique for maximizing generation of hydropower and meeting irrigation needs in the case of Koyna reservoir by means of NLP. While among various levels of dependable inflows, a 50% level of dependable inflows yielded increased hydropower generation of 4824.48 × 106 kWh in the absence of release constraints. Regulwar and Dabhade (2015) have developed a multipurpose reservoir model using the Python programming language. The developed model provides an optimal monthly operation policy. The optimization model gives 1503.73 Mm^3 for hydropower generation, 622.31 Mm^3 for irrigation and 19.075 Mm^3 for environmental flow to sustain river ecology. Ghimire and Reddy (2013) used an elitist –EM muted PSO technique for solving the weekly Reservoir operation model, which gives results of EMPSO, found the result in 3% more hydropower and found that the target hydropower of 4.8 GWH with a sustainability index of 0.75. Kumar and Yadav (2020) used Java Algorithm (JA), Invasive Weed Optimisation (IWO0 and DE (Differential Evolution). Algorithm use coded with MATLAB R 2014 b software. The model uses 75% dependability in flow, which was computed by the Weibull formula, the value of max. Hydropower generation by JA, DE, IWO. An Algorithm and the DE Algorithm achieved the best optimal solution compared to IWO. Compared to the mean optimal solution, DE performed better than JA and IWO. The genetic algorithm (GA) model has been used by Jothiprakash and Shanti (2006) in the Pechiparai reservoir, Tamil Nadu, India. For determining the optimal operational policy. A comparison was made between the actual demand, actual irrigation release, and GA models of various rule curves for the Pechiparai reservoir. GA Model is constrained by continuity, release and demand constraints. The irrigation release of the GA model was found to be equal to the irrigation requirement. Parlikar and Dahe (2020) have used simple GA to obtain an optimal solution from large data. But to cut down computation time in GA, they used GA-LP for the reservoir operation of Urmodi Reservoir.

The convergence of LP-GA is 20 – 25 % faster than in simple GA. The reservoir yield at 100 % reliability is calculated to be 187.965 MCM. Noori and Heydari (2013) have used GA in modelling the operation of the reservoir, the distribution of water amongst the different power houses, and reserving some part of the storage capacity for managing floods in multi-reservoir and multi-purpose reservoirs for hydropower production and flood control. The study of Shangwan (Shangwan, 2008) shows that proper application of optimization techniques can save 50 % water and damage. Comparing linear programming optimization (NLP) techniques is the study's goal. Genetic algorithms (GA) and collective intelligence (PSO) are used to manage agricultural water during dry spells in order to maximize revenue.

Kumar and Reddy (2007) applied GA, EMPSO and PSO techniques in deriving the operating policies for multipurpose reservoirs. The target of the reservoir objective is maximizing the electricity generation and minimizing the water. PSO shortage compared to EMPSO irrigation. The outcomes have shown that it can produce better results in extraction of reservoir exploitation policies. According to Salvi (2014), fuzzy logic has been used for the optimization of the reservoir operation in Jayakwadi dam for irrigation purposes. The irrigation releases at the maximum level of satisfaction are 590.40 $Mm^{3,}$ and the sum of the irrigation releases after the optimization by using FIS is 525.00 Mm^3. Devisree and Nowshaja (2014) have designed a GA-based model for developing an optimum multi-objective reservoir operation for Peechi Project, Kerala, India. The goal is to maximize the amount of power produced annually while taking into account reservoir storage limitations, irrigation demand, the storage continuity equation, and releases for power and turbine capacity. The maximum power generated through the developed programme is 3572200 kWh, and by the Matlab built-in tool is 3535000 kWh. And the maximum hydropower by LP solution is 3600000 kWh. Solutions provided by both Gas and LP have reasonable similarities. Annual hydro generation obtained by the GP and GA optimal model deviated from the LP solution by 0.8 % and 1.8%, respectively. Krishna and Umamahesh (2017), using MATLAB software, employed a GA-NLP hybrid approach in this study to determine the optimal rule curves and optimal release for the Nagarjuna Sagar reservoir for a variety of priority cases in irrigation and hydropower with two inflow conditions (75% PE & 80% PE). The yearly power generation has increased by 2.8%, and the irrigation deficit has slightly increased by 2% in scenario 1, Case III. In comparison to Case I, power generation has increased by 24%. Paliwal and Ghare (2017) developed an operating optimization model for the Mula reservoir in India's upper Godavari Basin. Performance in this model has been compared to GA, PSO, EMPSO, and WOA. Water releases proposed by the JA technique were better than those of other methods.

Regulwar and Choudhari (2010) have developed a multi-objective operational model for maximizing hydropower generation by the differential evolution algorithm (DEA). Based on the result from the implementation of the DE model, the maximum hydropower generation would be 30.885 × 106 kWh, while irrigation releases would be 928.44 Mm3. A genetic algorithm is employed as the comparative model, and the comparison between the results from GA and different DE approaches for irrigation release and hydropower generation reveals that the results are similar and comparable. Consequently, DE might be a different strategy for resolving a multipurpose reservoir's optimization issue. To create operational policies for a multipurpose reservoir with a single goal, Mathur (2016) applied the GA technique to the Upper-Wardha reservoir system. The optimal population size for the Upper Wardha reservoir is 250, and the likelihood of crossover is 0.75, according to the sensitivity analysis of the GA model for this specific reservoir.

Material and Methods

The Bhatsa River basin, an east-flowing river in the Western Ghats, is a significant right tributary of the Ulhas River. Its area is 736.343 km2. Only the big right bank tributaries, Kalu and Bhatsa, account for 55.7% of Ulhas' total catchment area. Major Project envisages the construction of two storage reservoirs, one of which is an earth-fill and gravity Bhatsa dam reservoir, which was constructed in 2005 on the confluence of the river Bhatsa and Chorona Ulhas Basin near the village Sajivali in Shahapur taluka, District Thane. It is a multipurpose dam; therefore, the first purpose of the Bhatsa reservoir is to provide an assured water supply for drinking to the Brihanmumbai Municipal Corporation at a rate of 1362 MLD. The second purpose is to provide irrigation facilities to 23000 Ha, and the third purpose is to generate 15 MW of electricity. It is a multipurpose project completed in 2005 with gross capacities (976.10 Mm^3) and Live storage capacities 942.10 Mm^3 and Dead storage capacity 34 Mm^3, respectively. During the non-monsoon season, the environmental flow is filled by adjacent subsurface water.

The system has two canals, i.e. 1. Bhatsa Right Canal having Length 54.00 km, which can irrigate around 7446 ha and the Left Bank Canal. Total Length - 17.00 km, which can irrigate 1774 ha, as well as 1346 Ha area is irrigated by Left Bank Canal from Mumari Dam. Along with this, there is the Barwadi Lift Irrigation Scheme, Tal. Shahapur, Dist. Thane, which can irrigate around 1267 ha. So the total gross command area is 10460 Ha. The ICA is an area of 9190 Ha spread over Shahapur, Kalyan, and Bhiwandi. Major crops grown in the command area are Paddy 4319 Ha (47 %), Nagili 1470 Ha (16%), Pulses 459.5 Ha (5%), Grass 2940.8 Ha (32%). A 15 MW pump storage power plant is located at the base of the dam in the reservoir. The entire command area is located in the eastern section of the state between latitudes 18°42' and 20°20' North and longitudes 72°45' and 73°48' East. 388.5 km2 is the entire catchment area. The location map of the study region is displayed in Fig. 1. The Bhatsa River Basin's irrigation area receives between 2000 and 4000 mm of rainfall annually from the South-West monsoons. The dates of it are June through September. Temperatures in the study region range from 16.3˚C to 26.5˚C at the lowest and from 28.0˚C to 35.2˚C at the highest. Bhatsa Reservoir receives an average of 783 MCM annually.

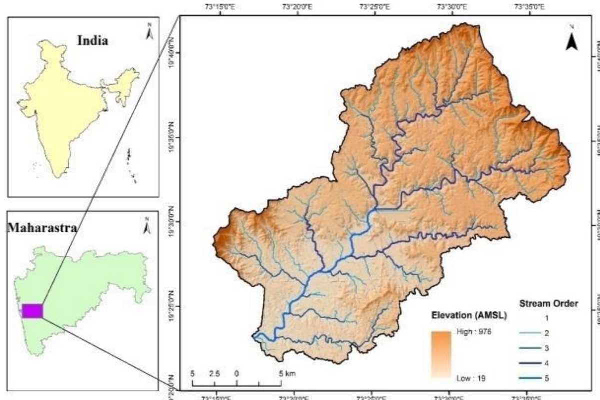

Fig. 1 Location map of hydro meteorological stations.

Data Collection

Monthly inflow and evaporation loss data

The historical data on a daily basis for all the months are collected from Bhatsa Reservoir, Bhatsa Officials of Bhatsa Nagar, Shahapur, Thane for the duration of 1996 to 2023. The monthly inflow data is calculated from recorded historical data.

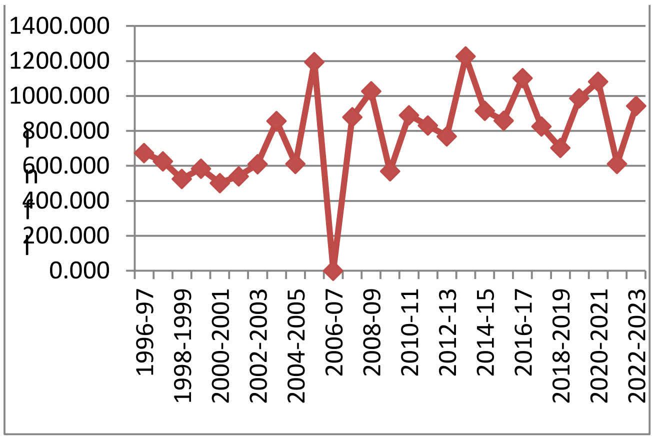

Fig. 2 Annual Reservoir Inflow of Bhatsa Reservoir

Table 1 Inflow and Different demands for reservoirs in MCM

Month	Bhatsa Dam Reservoir			
	Inflow	Maximum Irrigation Demand	Water supply demand	Hydropower Plant monthly demand
June	113.228	1.44	445.05	59.7
July	399.459	2.07	103.418	59.7
August	298.372	1.99	34.000	59.7
September	179.337	6.66	134.705	59.7
October	36.163	20.78	522.849	59.7
November	4.701	17.74	553.769	59.7
December	3.111	16.36	573.75	59.7
January	7.684	17.86	562.2	59.7
March	2.745	5.43	603.45	59.7
April	2.961	6.63	532.01	59.7
May	3.125	4.52	602.05	59.7
Total yearly	1053.67	108.09		656.7

Particle Swarm Optimization (PSO)

Based on the social behavior of flocks of birds, PSO is a population-based stochastic search technique used for optimization. Eberhart and Kennedy first presented PSO (1995). The PSO algorithm is based on people's social sharing of information. In order to find the best solution, the PSO algorithm randomly initializes the population, generates new solutions using the swarm update mechanism, and continuously improves its objective function across several iterations. However, in the PSO algorithm, particles fly in the search space having velocities dynamically altered depending on their previous behaviors. PSO algorithm can effectively deal with non-linear and non-convex problem domains, and it can also easily avoid the local optimum problem associated with non-linear optimization methods.

PSO Algorithm

PSO assigns a single dimension to each decision variable based on the number of decision variables in the problem. A random population (collection of solutions) is first constructed in order to initialize the model. The population is referred to as a swarm in PSO, and each member of the population is called a particle. The i^th particle can be represented as a D-dimensional vector in a D-dimensional search space, where a position vector represents the i^th particle. $X_i = (x_{i1}, x_{i2}, \dots \dots \dots x_{iD})^{T,}$ where D is the number of decision variables. The position of the particle changes according to its velocity. The velocity vector of the particle can be represented as $V_i = (v_{i1}, v_{i2} \dots \dots \dots v_{iD})^T$. During the execution of the model, the best position retained by the particle is stored. The best position of the i^{th} particle is represented by $P_i = (p_{i1}, p_{i2}, \dots \dots \dots p_{iD})^T$.

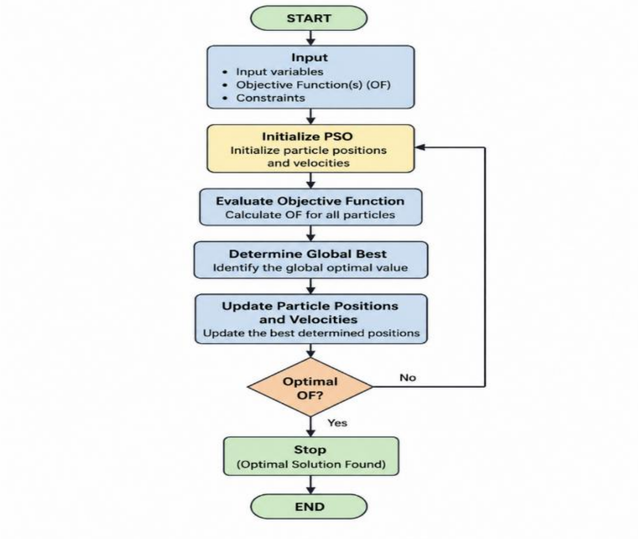

Fig. 3 Flow chart of the PSO model reservoir optimization

Model Development for Reservoir Optimization

The objective functions can be written as follows.

Objective 1: Maximization of Water Release for Irrigation (RI)

$Maximize\ Z_1 = \sum_{t=1}^{12} RI_t$ … (1)

Where, RI_t is irrigation water release during month t (MCM) and t is monthly time step ($t = 1, 2, 3, \dots\dots, 12$)

Objective 2: Maximization of Water Release for Hydropower Generation (RP)

$aximize\ Z_2 = \sum_{t=1}^{12} RP_t$ …(2)

Where, RP_t is water release for hydropower generation during month t (MCM), and t is the monthly time step ($t = 1, 2, 3, \dots\dots, 12$)

The goal of the reservoir operation model is to maximize discharges at a monthly time period, subject to a number of operational and physical limitations. An optimization tool is used to solve the aforementioned model for maximization. The following are the specifics of the mathematical model used to create the best operational guidelines for a single multifunctional reservoir system in the Bhatsa River sub-basin.

System Constraints

The following system restrictions affect the aforementioned objective functions:

Mass Balance equation: - The reservoir system follows the mass balance equation as follows

$S_{t+1} = S_t + Q_t - R_t - DQ_t - Ev_t - O_t$ for all $t = 1,2,3 \dots, 12$ Months …(3)

Where S_t and S_{t+1} are the starting and ending reservoir storage volumes in Mm³ at a monthly time period. $Q_t, R_t, DQ_t, Ev_t\ and\ O_t$ are the inflow, releases, downstream environmental flow, evaporation loss and overflow (Mm³).

The reservoir design must take into account the environmental flow since it is crucial to preserving the river's and its ecosystem's health. Since there will be enough water available from the spring sources, the provision of environmental flow (RE_EF) is regarded as zero. The environmental flow must be greater than or equal to the minimum flow during the non-monsoon season. The minimum environmental flow should be regarded as 0.5% of the 75% reliable flow, according to the CWC study report's recommendations. The environmental flow is limited by and calculated in accordance with CWC criteria.

$RE_{EF} = 0.005 \times Q_{75} \quad \forall t = 1,2,3, \dots, 12$ …(4)

Where

RE_{EF} = required environmental flow,

Q_{75} = 75% dependable annual flow,

t = monthly time step.

The irrigation releases during any month (RI) should be less than or equal to the maximum irrigation demand and should be greater than or equal to the minimum irrigation demand

$(RI)_t \ge ID_{min}$ ID_{min} = Minimum irrigation demand

$(RI)_t \ge ID_{max}$ ID_{max} = Maximum irrigation demand

The capacity of the turbine installed in the power house for the production of hydroelectric electricity determines the constraints for turbine release. The amount of water discharged from the reservoir must match or exceed the amount of water needed to generate the least amount of electricity. When producing electricity, water outflows should be larger than or equal to firm power and less than or equal to turbine capacity.

RP (i, t) ≤ TC (i) ∀i = 1, 2, 3, 4 ,…….,12.

RP (i, t) ≥ FP (i) ∀t = 1, 2, 3,……, 12.

Reservoir storage (S) for all months should be less than or equal to the maximum reservoir storage capacity (SC_{max}) of the reservoir and should be greater than or equal to the minimum storage capacity (S_{min}) of the reservoir. It can be given as:

$$S_{min}(i) \le S(i,t) \le SC_{max}(i);\ \forall\ t = 1,2,3, \dots, 12$$

When the final storage in any month exceeds the capacity of the reservoir, the constraint is given by

$Q_t = S_{t+1} - S_{\max}$ $t = 1,2,3, \dots\dots 12$ and $O_t > 0, t = 1,2,3, \dots\dots, 12$

O_t= Surplus from the reservoir during the month.

Constraint of Hydrologic Continuity

The continuity constraints involve releases, overflows, storages, inflows and losses through the reservoir during the time period t. Time period t represents the monthly. The evaporation losses are expressed as a function of storage. The storage continuity equation is given below.

$$S(T) + IN(T) - RE_{IRR(T)} - RE_{POW(T)} - OVF(T) + FCR(T) - RWS(T) - E(T) = S(T+1) \quad \ldots(5)$$

IN = inflow in the reservoir during the month t, $S(T)$ = reservoir storage at the start of the month. $S(T+1)$ = reservoir storage at the end of the month $T+1$, i.e. storages in the next month; $RE_{IRR(T)}$ = Releases for irrigation; OVF = the overflow from the reservoir during the month t; it should be greater than zero; $E(T)$ = Average evaporation from each rate.

Result and Discussion

In the current research, the Linear programming (LP) model has been developed by considering a 25% dependable inflow estimated by Weibull's method. The model was utilized in the case study of Bhatsa Multipurpose Reservoir by considering all the constraints (Max Irrigation and Min irrigation demand, evaporation losses, turbine capacity, and firm power) to obtain the optimal release policies. The developed model is solved in LINGO / Glober solver to maximise releases for hydropower production. The constraints of optimization model are: 1) Turbine capacity = 15 MW, 2) Gross storage capacity = 976 M m^3, 3) Dead storage capacity =34 Mm^3, 4) Firm power = 4.5 MW.

Optimal Monthly Canal Release by LP model

The optimal monthly canal releases and gross storages at the end of every month obtained from the LP model are given in Table 2. Significant inflows occur mainly during the monsoon period (June–September), with the highest inflow recorded in July (~399 MCM). The amount of surface water utilized for optimal releases is 1053.637 Mm^3. The maximum and minimum release for irrigation are 20.78 Mm^3 and 1.44 Mm^3 in the months of October and June.it demonstrates that the least amount of surface water is used in June, July, and August because of the low demand for irrigation brought on by precipitation. The linear programming model achieved a global optimal solution with a total reliable irrigation supply (TOTRE_IRR) of 108.09 million cubic meters (MCM) over the entire year, while simultaneously supplying 59.7 MCM for reliable power generation (TOTRE_POW). Overflow (OVF) occurs only in the early monsoon months (June ~36.7 MCM and July ~23.8 MCM); no overflow occurs from August onwards.

The reservoir maintains a minimum storage of 34 MCM during the monsoon months (June–July) and gradually builds up to peak storage of approximately 732 MCM in October. This is less than the maximum storage capacity of 996 Mm^3 of the reservoir. No Feeder canal releases (FCR) are required in any month under the optimal policy. The model successfully satisfies all minimum irrigation demand constraints (IRRD_MIN), maximum allowable irrigation releases, storage bounds, and reliability commitments for both irrigation and power, without any infeasibility. Overall, the optimized operation plan ensures reliable delivery of 108.09 MCM of irrigation water and 57.9 MCM for power generation annually, while effectively managing reservoir storage and minimizing unnecessary spill during the water year.

Table 2 Monthly irrigation releases and storages (MCM) in the reservoir at the end of every month from Bhatsa reservoir by (Optimization tool)

Month	Inflow	Releases				Gross Storage
		Spill (Overflow)	Irrigation	Hydropower	Evaporation loss	
Jun	113.228	36.70	1.44	59.7	1.48	34
July	399.459	23.80	2.07	59.7	0.43	34
Aug	298.372	0.00	1.99	59.7	0.82	355.15
Sept	179.337	0.00	6..66	59.7	1.27	637.212
Oct	36.163	0.00	20.78	59.7	2.56	732.119
Nov	4.701	0.00	17.74	59.7	2.08	659.442
Dec	3.111	0.00	16.36	59.7	2.54	549.823
Jan	7.684	0.00	17.86	59.7	2.72	443.234
Feb	2.751	0.00	6.61	59.7	2.48	354.768
Mar	2.745	0.00	5.43	59.7	3.13	278.929

Aprl	2.961	0.00	6.63	59.7	3.44	196.814
May	3.125	0.00	4.52	59.7	3.31	116.205
Annual	1053.637		108.09			

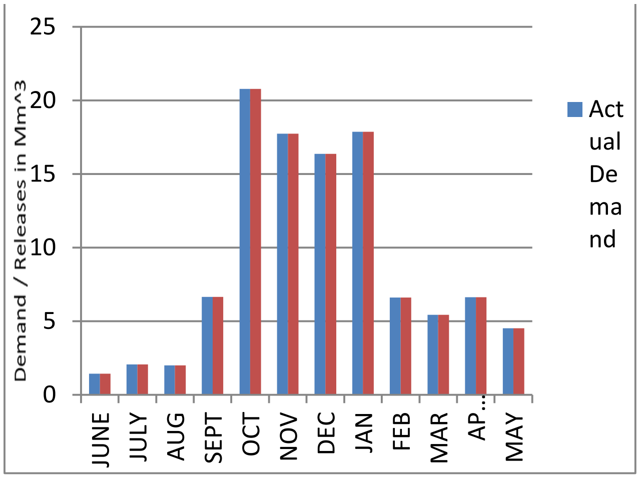

Fig. 4 Demand vs. releases by optimization tool

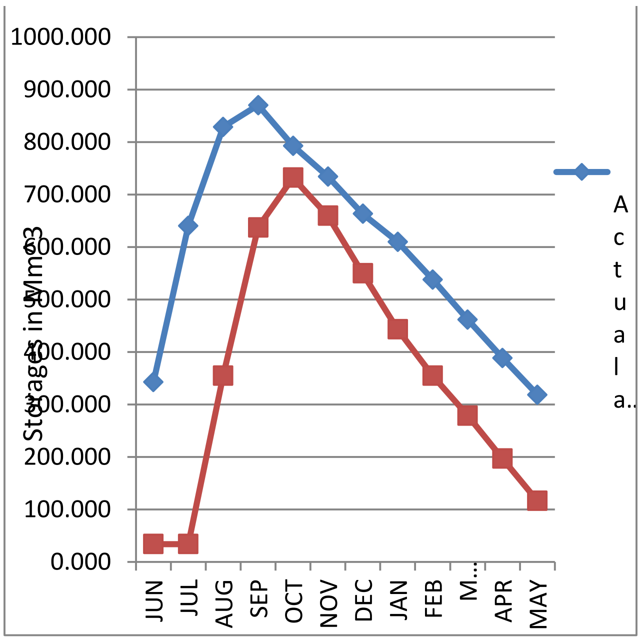

Fig. 5 Reservoir storage policy obtained by optimization tool

The graph compares monthly storage levels in the Bhatsa reservoir (June–May) using two lines: the blue line represents actual average historical storage, starting low in June (320 Mm³), rising sharply to a peak of 900 Mm³ in August due to monsoon inflows, and gradually declining to 300 Mm³ by May. Reflecting conventional operations prone to spills and shortages. The red line shows optimized storage from a linear programming tool, beginning near dead storage (50 Mm³) in June, building more conservatively to 700 Mm³ in September, and steadily declining to near zero by May. This optimization prioritizes maximum irrigation releases and hydropower while respecting minimum storage constraints (34 Mm³), resulting in lower but more stable and efficient utilization with reduced spills. Key insights include faster/higher monsoon filling in actual operations versus controlled releases in the optimized policy, smoother dry-season drawdown in the latter, and overall benefits in balancing demands (irrigation 1–20 Mm³/month, hydropower 15 Mm³/month) without bound violations.

PSO Model

After successful implementation of the optimization model in MATLAB software through the application of Particle Swarm Optimization (PSO), the results obtained were compared to those obtained through the LINGO optimization model for the same objective function. The model output comprises graphs for the model convergence, optimal objective function value, monthly reservoir operation policy, and optimal irrigation and power release schedule. The PSO performance is determined by the appropriate choice of algorithm parameters, mainly population size and maximum number of iterations. These parameters have a great influence on the convergence process and the nature of the optimal solution. The PSO model in this study was implemented with a population size of 75 particles, 50 maximum iterations and 12 decision variables (monthly irrigation releases (RE_IRR) during one year). The cognitive and social acceleration parameters were set at 1.5 and 2.0, respectively. A single optimization run was carried out in this case. From previous trial runs using different populations and iteration numbers, it was noted that a combination of 75 particles and 50 iterations produced good convergence behavior.

A MATLAB-based PSO model was constructed employing the same input data and constraints considered in the linear programming (LINGO) model in order to make a direct comparison between the two models. In the first step of optimization process, the objective function was set at the maximization of the irrigation releases with all operational constraints and allocation priorities satisfied. The solution for the problem was obtained successfully after 50 iterations, with the fitness value being 29,820.0. The hydrological study shows that the inflows into the reservoir are considerable during the monsoon season (June-September), with the highest monthly inflow being about 399 MCM in July. The optimized reservoir operation employs about 1,053.64 MCM of surface water in the entire year. The monthly irrigation releases range from 1.44 MCM to 17.74 MCM, with the minimum release being in June while the maximum is in November. The low irrigation releases in June, July, and August are because of the presence of rainfall during the monsoon season.

The optimal operation gives the Total Reliable Irrigation Supply (TOTRE_IRR) of 101.09 MCM in the course of a one-year planning period, along with the Total Reliable Hydropower Release (TOTRE_POW) of 59.70 MCM. During the simulation process, there is no spillage through the spillway, which indicates the effective use of the reservoir storage volume. The Reservoir Storage is kept at around 34 MCM during the early part of the monsoon period (June to August) and then gradually increases with the inflows and reaches the maximum of around 976 MCM in October/November.

The proposed optimal operating policy fulfils all the constraints of the system, including minimum irrigation demands (IRRD_MIN), maximum irrigation releases, storage capacities, mass balance, and reliability constraints of both irrigation and hydropower generation. In general, the PSO-based Reservoir Operation model shows an efficient use of available water resources in the sense that it provides an optimization of the irrigation releases along with reliable hydropower generation and maintains the reservoir storage within permissible limits without spillages.

Table 4 Particle swarm optimisation results of monthly releases

Month	Inflow (Mm^3)	Releases (Mm^3)				Gross Storage (Mm^3)
		Spill (Overflow)	Irrigation	Hydropower	Evaporation loss	
JUN	113.228	0.00	1.44	59.7	1.48	34.00
JULY	399.459	0.00	2.07	59.7	0.43	976.00
AUG	298.372	0.00	1.99	59.7	0.82	34.00
SEPT	179.337	0.00	6.66	59.7	1.27	760.296
OCT	36.163	0.00	15.22	59.7	2.56	976.100
NOV	4.701	0.00	17.74	59.7	2.08	976.100
DEC	3.111	0.00	16.36	59.7	2.54	34.000
JAN	7.684	0.00	17.86	59.7	2.72	251.008
FEB	2.751	0.00	6.61	59.7	2.48	777.917
MAR	2.745	0.00	5.43	59.7	3.13	976.000
APRL	2.961	0.00	6.63	59.7	3.44	976.100
MAY	3.125	0.00	3.16	59.7	3.31	34.00
Annual	1053.637		101.156			

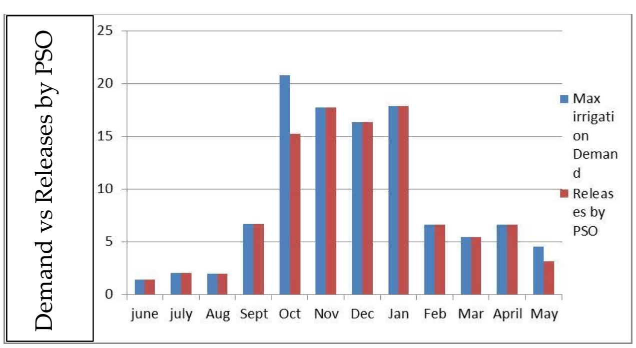

Fig. 6 Demand vs. Releases by PSO

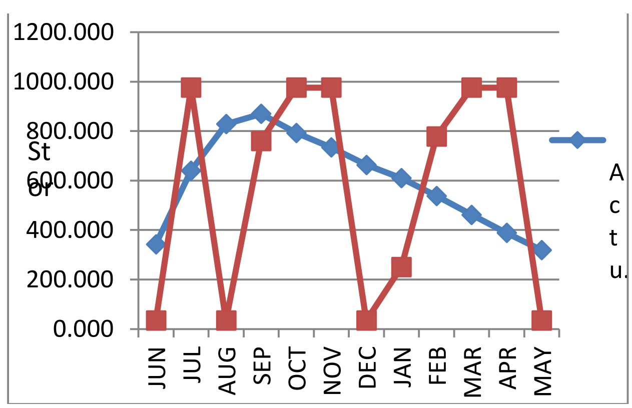

Fig. 7 Reservoir storage policy obtained by PSO

The above graph illustrates the monthly storage patterns in the Bhatsa reservoir over a water year (June–May), comparing actual average storage (blue line) with storage optimized via the Particle Swarm Optimization (PSO) algorithm (red line). The actual storage starts low in June (~330 MCM), rises sharply to a peak of 900 MCM in July due to monsoon inflows, but exhibits volatile fluctuations and a steep decline in dry months, potentially indicating inefficiencies like uncontrolled spills or shortages. In contrast, the PSO-optimized storage maintains consistently higher levels, peaking at 976 MCM in July and showing more pronounced but strategic variations to maximize hydropower releases (fixed at 15 MCM /month) while adjusting irrigation releases (RE_IRR) to avoid storage violations (e.g., below 34 MCM dead storage). This results in better sustainability, with PSO ending the year at higher reserves (~200 MCM in May) compared to actual (976 MCM), demonstrating its effectiveness in balancing multipurpose demands. Overall, the graph concludes that PSO, as implemented in your MATLAB script, outperforms traditional operations by enhancing reservoir reliability and efficiency.

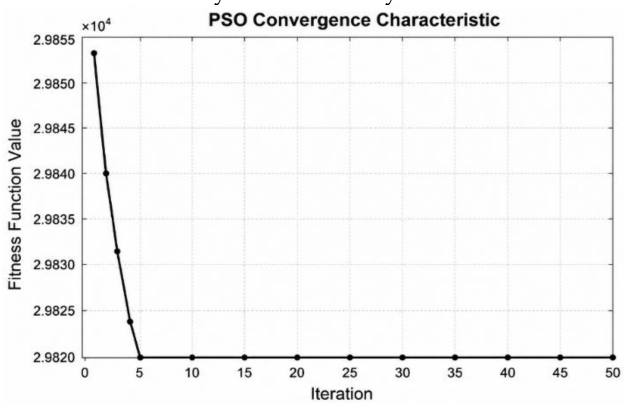

Fig. 8 PSO convergence curve

The image displays a line graph titled "PSO Convergence Characteristic," plotting the Fitness Function Value on the y-axis (ranging from about 2.982 to 2.985 × 10^4) against Iteration on the x-axis (from 0 to 50). It illustrates a rapid initial decrease in fitness value over the first few iterations, followed by stabilization at a constant value around 2.982 × 10^4, signifying that the Particle Swarm Optimization (PSO) algorithm quickly converges to an optimal or near-optimal solution.

This convergence pattern indicates efficient exploration and exploitation of the search space in the optimization process, typical for PSO in solving complex problems. In conclusion, the graph highlights the effectiveness of PSO in achieving stable results early, as evidenced by the flat line after iteration 5, while the accompanying MATLAB output shows a maximized total RE_POW of 180 at 15 per month with varying RE_IRR and storage levels, contrasting with the LINGO LP solution that prioritizes higher total RE_IRR of 108.09.

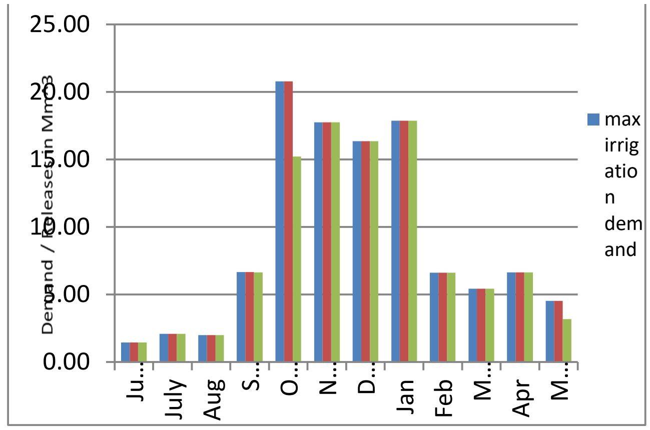

Fig. 9 Irrigation Demand Vs. Irrigation Release from Bhatsa Dam

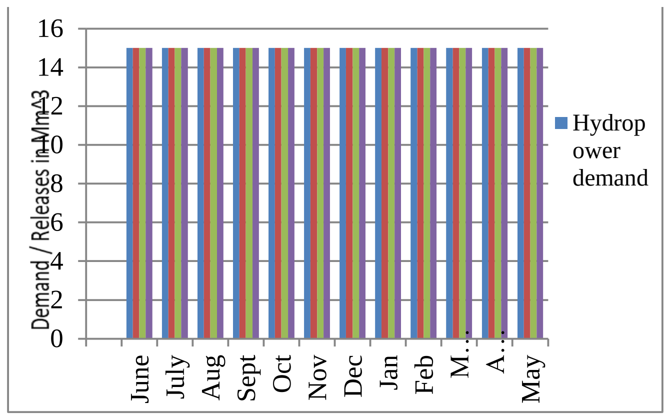

Fig. 10 Hydropower demand vs. hydropower releases

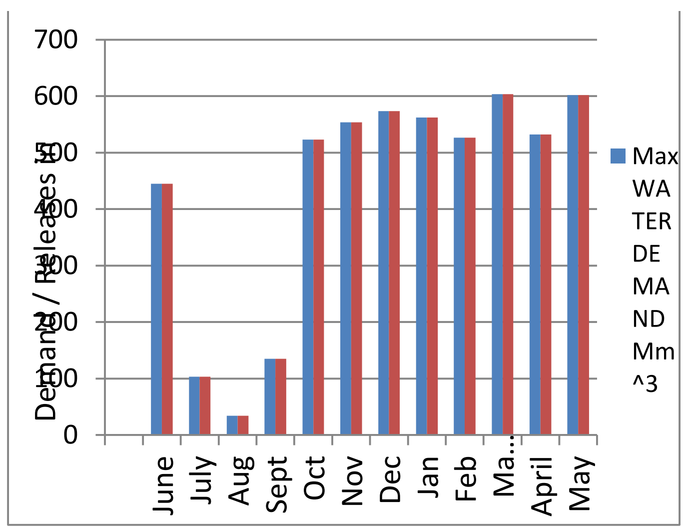

Fig. 11 Water demand vs water release from Bhatsa Da

Conclusions

In the present study, a reservoir operation model for the Bhatsa reservoir in Maharashtra, India, was developed using LINGO and PSO, achieving maximization of irrigation releases at 108.9 Mm^3 and hydropower generation at 57.9 Mm^3 in LINGO, with PSO results proving comparable for practical use. The LINGO LP solver yielded a global optimal TOTRE_IRR of 108.09, fully satisfying irrigation demands (100%), while PSO delivered 101.143 Mm^3 total irrigation releases, meeting 100% of maximum demands in most months (June–September, November–April) but only 80% in October and 75% in May. Both models shared parameters like storage capacity (976.10) and minimum storage (34.0), yet differed in monthly RE_IRR (e.g., October: 15.224 in PSO vs. 20.78 in LINGO) and storages (e.g., August: 34.000 in PSO vs. 355.15 in LINGO), with PSO prioritizing hydropower maximization (total RE_POW 180.000 MCM at 15.000/month) and LINGO focusing on irrigation under firm power constraints (4.5/month). Minimum storage occurred at the monsoon start (end of water year), peaking mid-monsoon. Both achieved an optimal objective of -180.000 for RE_POW with identical values, but LINGO converged faster (3 iterations, 0.06 seconds) than PSO (50 iterations, 0.162143 seconds), offering additional insights like reduced costs and dual prices. Maximum water demand is deemed optimal for releases, making LINGO ideal for linear problems and PSO better for nonlinear scenarios.

Future Scope

1. A combination of genetic algorithm and particle swarm optimization, hybrid model can be applied to the case study.
2. Due to uncertainties of climate change impacts on future reservoir operation policy under different climatic scenarios in accordance with global climate change strategies.

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Data Availability Statement

The data set generated during the current study is taken from Bhatsanagar Bhatsa Official, Shahapur Thane.

Conflict of Interest

The authors declare they have no known competing financial interests or personal relationships regarding the publication of this paper.

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