CE718: WATER RESOURCES SYSTEMS ANALYSIS

Optimized Water Allocation from Hirakud Dam for Irrigation, Hydropower, and Sustainable Industrial Use

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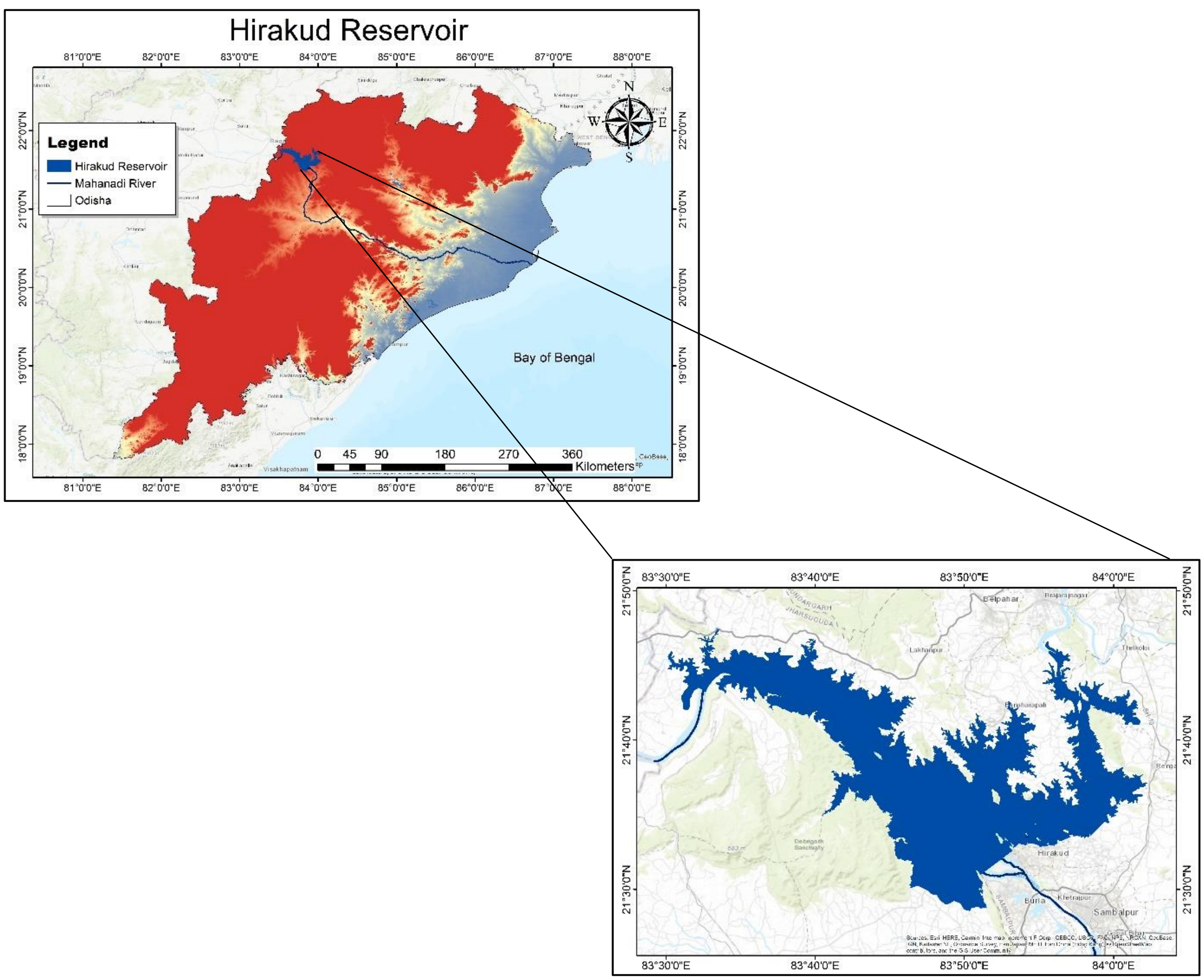
Hirakud Reservoir

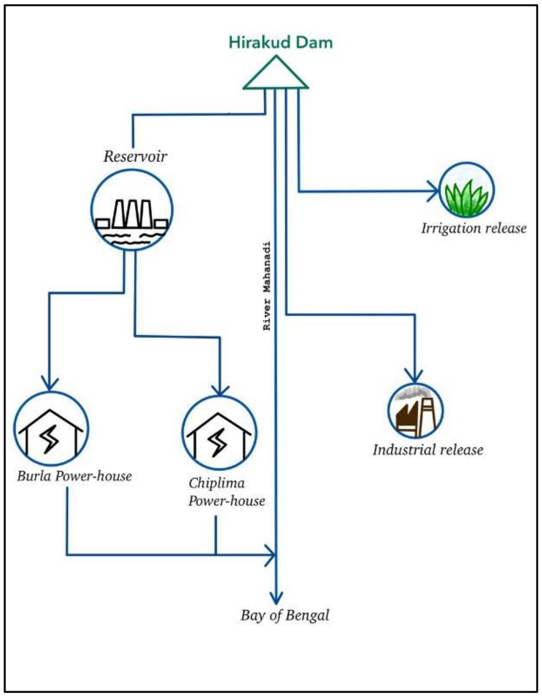
This project presents a case study of optimal allocation of water for irrigation and power generation at Hirakud reservoir with the application of genetic algorithm. Hirakud is a multi-purpose project, which is situated in the Sambalpur district of Odisha, India. As the inflow to the reservoir is uncertain, it usually creates difficulties in dealing with reservoir operations. Here we have tried to optimize the reservoir operation with an aim to minimize irrigation deficit, maximize power generation and minimize industrial allocation. We used non-traditional techniques, such as genetic algorithms, to handle the complexity and non-linearity of supply and demand.

Study area

The Hirakud Reservoir, located in the Sambalpur district of Odisha, India, is one of the oldest and largest multipurpose river valley projects in the country. Constructed across the Mahanadi River, the dam plays a crucial role in regional water resource management, supporting irrigation, hydropower generation, and limited industrial water supply. The reservoir has a gross storage capacity of 8.136 billion cubic meters and caters to a command area spread across multiple districts. The region experiences a tropical climate, with monsoon rainfall contributing significantly to reservoir inflow.



Network diagram



Model equations

Decision Variables: x_t^{ir} **,** x_t^{p}**,** x_t^{in}

Objective Function:

Minimize irrigation demand-release deficit and maximize hydropower:

Minimize $\sum_{t=1}^{12} \left(D_t - x_t^{ir} \right)^2$ (Irrigation demand deficit)

Maximize $\sum_{t=1}^{12} 0.00378 \cdot \eta \cdot H_t \cdot x_t^{p}$ (Hydropower generation)

Minimize $\sum_{t=1}^{12} x_t^{in}$ (Industrial supply)

Where:

D_t: Irrigation demand in month t

x_t^{ir}: irrigation release in month t

x_t^{p}: power release in month t

x_t^{in}: industrial release in month t

Subject to:

1) Water budget equation:

$$(1 + 0.5ae_t)\, S_{t+1} = Q_t - R_t - e_t A_0 + S_t(1 - 0.5ae_t)$$

Where:

Qt = Inflow to the dam

et = Evaporation rate

$A0$ = Initial Area (at MDDL)

Rt = Release from the dam

St = Storage at stage t

a =the surface area per unit storage

2) Release:

$$R_t = x_t^{ir} + x_t^{p} + x_t^{in}$$

$$R_t \geq 0$$

3) Storage for starting of next year

$$S_{13} \geq S_1$$

4) Storage bounds:

$$Smin \leq S_t \leq Smax$$

5) Minimum flood storage capacity:

$$Smax - S_t \geq F_{min}$$

Where:

t= 7 (july month)

Smax: Gross storage capacity of the reservoir

Fmin : Minimum required flood storage capacity

6) Storage for months of low inflow:

St > storage_min + Sbuffer

t in [0, 1, 2, 3, 4, 5]

*This is done as the storage falls below minimum even after adding penalty

7) Industrial demand bounds:

$$0 \leq x_t^{in} \leq \text{Max\_industrial\_allocation}$$

8) Power and Canal Constraints:

$$0.00378 * \eta * H_t * \leq P_{max}$$

Where:

Pmax : Maximum allowable hydropower output (in MW)

Ht : Net head (Ht is a function of Storage)

η : Efficiency of turbines

9) x_t^{ir} $\leq$ Canal Capacity

10) Min Demand $\leq$ x_t^{ir} $\leq$ Max Demand

11) Min Release $\leq$ x_t^{p} $\leq$ Max Release

12) Non negativity of decision variables x_t^{ir},x_t^{in}, $x_t^{p} \geq 0$

Multi-objective Optimization

Minimize: $\omega_1 * \sum_{t=1}^{12} (D_t - x_t^{ir})^2$

$- \omega_2 * \sum_{t=1}^{12} 0.00378 \cdot \eta \cdot H_t \cdot x_t^{p}$

$+ \omega_3 * \sum_{t=1}^{12} x_t^{in}$

where t is 1 to 12 months

Software and Method: We used the **DEAP** Python module to implement a multi-objective Genetic Algorithm (NSGA-II) in this optimization problem. The monthly releases of 12-month period are optimized. In this implementation we have taken: Population size: 100-200, generations:30-50, crossover probability: 0.7, mutation probability:0.2 each individual encoded as a vector of 36 decision variables.

Code: water_res_pr (3).py

Results and discussion

The system manages water for three competing purposes: irrigation, hydropower generation, and industrial supply.

Weightage (w1,w2,w3)	Irrigation Deficit (MCM^2)	Hydropower (MW)	Irrigation Release (MCM)
(0.33, 0.33, 0.33)	738.75	445.37	2004.23
(0.70, 0.10, 0.20)	190.98	294.99	1823.11
(0.30, 0.40, 0.30)	615.27	408.10	1599.68
(0.20, 0.10, 0.70)	1809.80	374.02	979.68

Table 1

Table 1: shows sum of irrigation deficits, hydropower production and industrial supply for whole year. When more weightage was given to irrigation deficit, we saw minimum hydropower generation and high industrial release. When we increased the weightage to reduction of

industrial release, there was still prominent irrigation deficit and moderate hydropower generation. Prioritizing one always comes at the expense of other objectives.

Fig 1,2,3 and 4 shows 4 plots each for irrigation, hydropower and industrial releases, irrigation demand and supply comparison, Storage trajectory and hydropower generation for 12-month period when assigned different weightage to all three optimization functions.

Fig 1: Emphasizing minimization of industrial supply. The plot shows significant reduction in industrial release It also shows major power release during monsoon months; storage utilization was prominent in 7-11 months and irrigation deficit in march, June and October months.

Fig 2: Emphasis on hydropower generation. The plot shows that it starts with high power release but fluctuates throughout the year, better irrigation demand supply difference except in non-monsoon periods, and industrial release was also controlled. The storage trajectory was still same.

Fig 3: A balanced approach where equal weightage was given to each objective. The irrigation deficits appeared to be not very significant while hydropower generation was quite variable throughout the year. Industrial release was comparatively at lower level. This plot showed how all the objectives were achieved without much affecting the other.

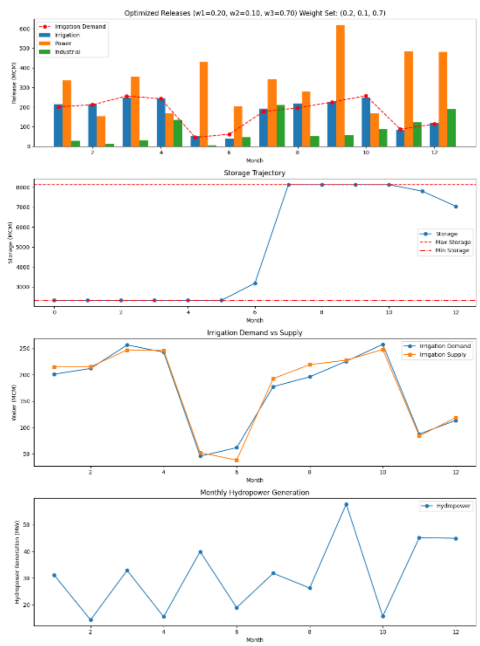


Fig 1

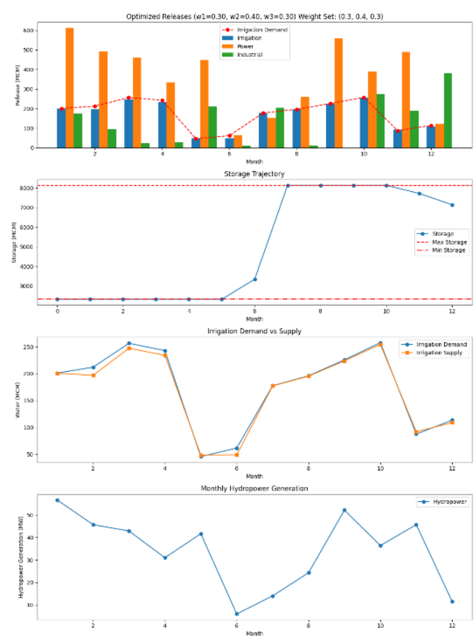
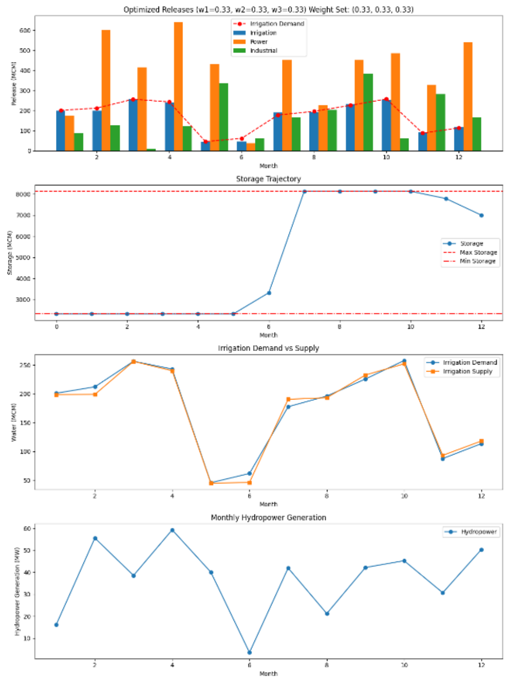


Fig 2



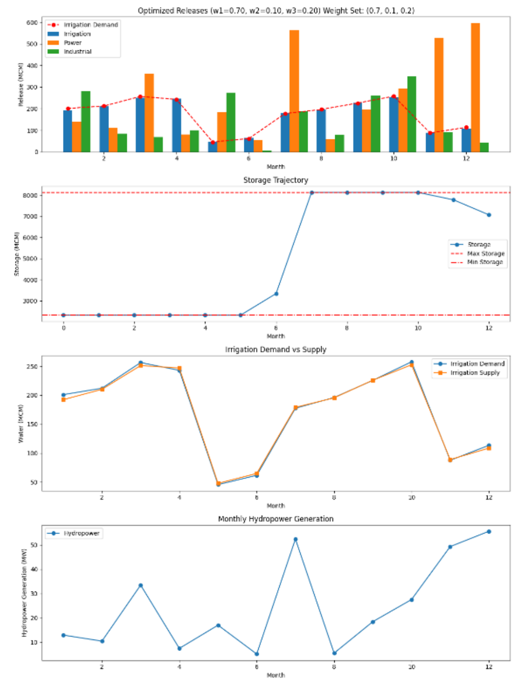
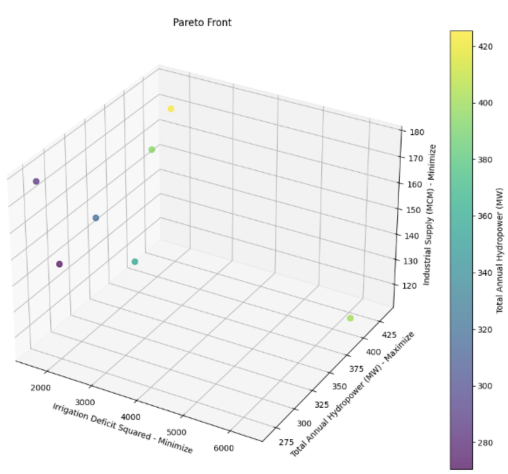


Fig 3

Fig 4

Fig4: This optimization heavily prioritizes minimizing irrigation deficit. The plot shows better fulfillment of irrigation needs. This is the result of trade- off optimization that shows high hydropower generation and industrial water release gets curtailed.

The spillway discharge patterns in each scenario are almost the same. This implies that flood management, irrespective of operational priorities, has little flexibility.



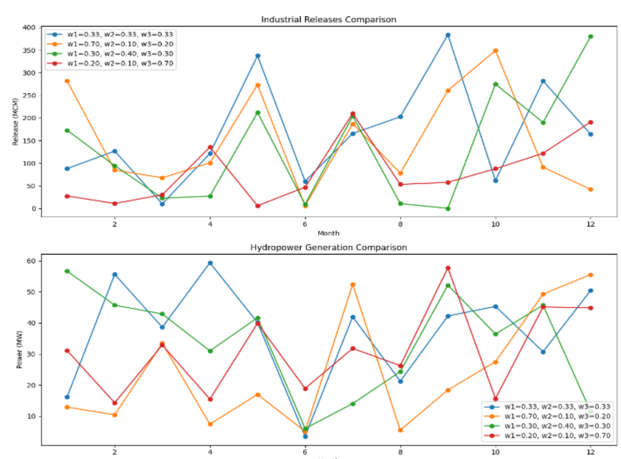


Fig 5

Fig 6

Fig 5: The pareto front clearly shows the trade-offs between irrigation deficit on x axis, power generation on y axis and industrial water allocation on z axis. The color shows different range of hydropower production.

Power release: Large variation in non-monsoon periods. The fluctuation among different weighting systems indicates how prioritizing influences production over a year. Results show best with higher power weights but reduced when given priority to irrigation.

Fig 6: Industrial Release Variation**:** Significantly less release in initial months, and more variation in non-monsoon periods for different weightages. Midyear clearly depicts short convergence in all approaches.

Conclusion

The Genetic algorithm technique excels at handling multiple competing objectives simultaneously by maintaining a set of Pareto-optimal solutions. This population-based framework has its limitations. This computationally intensive method produces variable outcomes due to its dependency on randomness, rather than providing a single optimal solution.

The water management problem we focused on was three distinct optimization scenarios of Hirakud dam. The plots reveal some remarkable consistency in certain aspects despite the varying weights. The reservoir follows the same annual cycle of maintaining minimum storage at initial months, then rapid increase, reaching capacity at 7-10 month and at the end a controlled reduction. Instead of employing static weights all year round for Hirakud Dam,

I suggest a dynamic three-phase management approach based on the examination of four distinct optimization scenarios. In order to ensure that crop demands are satisfied throughout crucial growing times, the initial phase (months 1–5) should prioritize agricultural needs with a heavy weight favoring irrigation. In order to greatly reduce the enormous spillage incidents that are now occurring, weights should be shifted to emphasize hydropower generation during the monsoon season (months 6–8) while adopting pre-releases to establish flood storage capacity. In order to maximize release across all sectors and being ready for next seasonal months, the last phase (months 9–12) should employ balanced weights. This will ultimately increase system efficiency and lessen resource conflicts.

Data Sources: -

1. **Storage Capacity of Hirakud Dam:-** The gross storage capacity, live storage and dead storage capacity of Hirakud Dam is taken for year 2001 from official website of Odisha Hydro Power Corporation Ltd. *(source:-https://www.ohpcltd.com/Hirakud/waterturbine)*
2. **Quantity of water consumed by different industries:-** The quantity of water consumed by different industries in 2015 was sourced from a study by Satapathy and Satapathy (2015)*(source:- https://ijarse.com/images/fullpdf/1435250471_17_Research_Paper.pdf)*
3. **Industrial limit:-** Hirakud dam was mainly built for irrigation and hydropower generation. So, the maximum permissible industrial water withdrawal limit during the approval of the Hirakud Dam was sourced from a credible news article titled *"Water drawal by industries from Hirakud within limit"* published by *Business Standard*.*(Source:* https://www.business-standard.com/amp/article/companies/water-drawal-by-industries-from-hirakud-within-limit-109112400051_1.html*)*
4. **Tailwater level of dam:-** Information regarding tailwater level of dam was referenced from the paper available at Utah State University's Digital Commons.*(source:-https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1540&context=ishs)*
5. **Inflow to Hirakud dam and irrigation demand**:- Monthly inflow and irrigation demand for Hirakud reservoir is sourced from a study titled "Optimal Reservoir Operation Using Fuzzy Approach"(S*ource:-https://www.researchgate.net/publication/250459620_OPTIMAL_RESERVOIR_OPERATION_USING_FUZZY_APPROACH?enrichId=rgreq-0895ab7eb076419349850e5d7968d717-XXX&enrichSource=Y292ZXJQYWdlOzI1MDQ1OTYyMDtBUzoxMDExMTc4ODcyNTQ1MzhAMTQwMTExOTc5MTgxMA%3D%3D&el=1_x_3)*
6. **Temperature data:-** The average monthly temperature data for Hirakud dam over a 12yr period has been taken from World Weather Online*(Source:-https://www.worldweatheronline.com/hirakud-weather-averages/orissa/in.aspx)*
7. **Canal Capacity:-** The maximum discharge carrying capacity of all three canals originating from the Hirakud Dam—**Bargarh Main Canal**, **Sason Main Canal**, and **Sambalpur Distributary**—has been sourced from the study *"Impact of Environmental Pollution in Hirakud Reservoir: A Critical Analysis with Special Emphasis on Pisciculture"(Source:-* https://www.vsrdjournals.com/pdf/VSRDIJTNTR/2018_2_February/5_Ramakanta_Satapathy_VSRDIJTNTR_13709_Research_Paper_9_2_February_2018.pdf)
8. **Rainfall data:-** The rainfall data for Hirakud Reservoir has been obtained from the India-WRIS(Water Resources Information System) Portal. The dataset includes historical rainfall records specific to the reservoir's location and is used for analysis and modelling purposes.(*Source:-https://indiawris.gov.in/wris/#/Reservoirs*)
9. Data of rainfall and Evapotranspiration rate Data_rain_et.xlsx

10. **Release for power generation:-** The data related to water release for power generation from the Hirakud Dam has been obtained from the study *"Water allocation from Hirakud Dam, Odisha, India for irrigation and power generation using optimization techniques"* by Ashutosh Rath and Prakash Chandra Swain, published in the *Journal of Water and Land Use Management* (). This study provides detailed insights into historical water release patterns which is instrumental in modeling and optimizing power generation scenarios
(Source: https://www.tandfonline.com/doi/full/10.1080/09715010.2018.1548308#d1e1065)
11. **Initial Storage of Reservoir:-** The initial storage data for the Hirakud Reservoir has been obtained from the study *"Temporal Analysis of Area-Capacity Curve for Hirakud Reservoir"*.(Source: http://ethesis.nitrkl.ac.in/5803/1/E-18.pdf)
12. **Turbine Efficiency:-** The turbine efficiency data has taken from official website of Odissa Hydro Power Corporation Ltd. This information provides key operational parameters necessary for accurately model the power generation process power (Source: https://www.ohpcltd.com/Hirakud/waterturbine)