PROJECT TITILE

OPTIMIZATION OF HIRAKUD DAM OPERATION USING GENETIC ALGORITHM FOR FLOOD CONTROL AND DEMAND MANAGEMENT

Course: **CE718 – Water Resources Systems Engineering**
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Date: 20 April,2025

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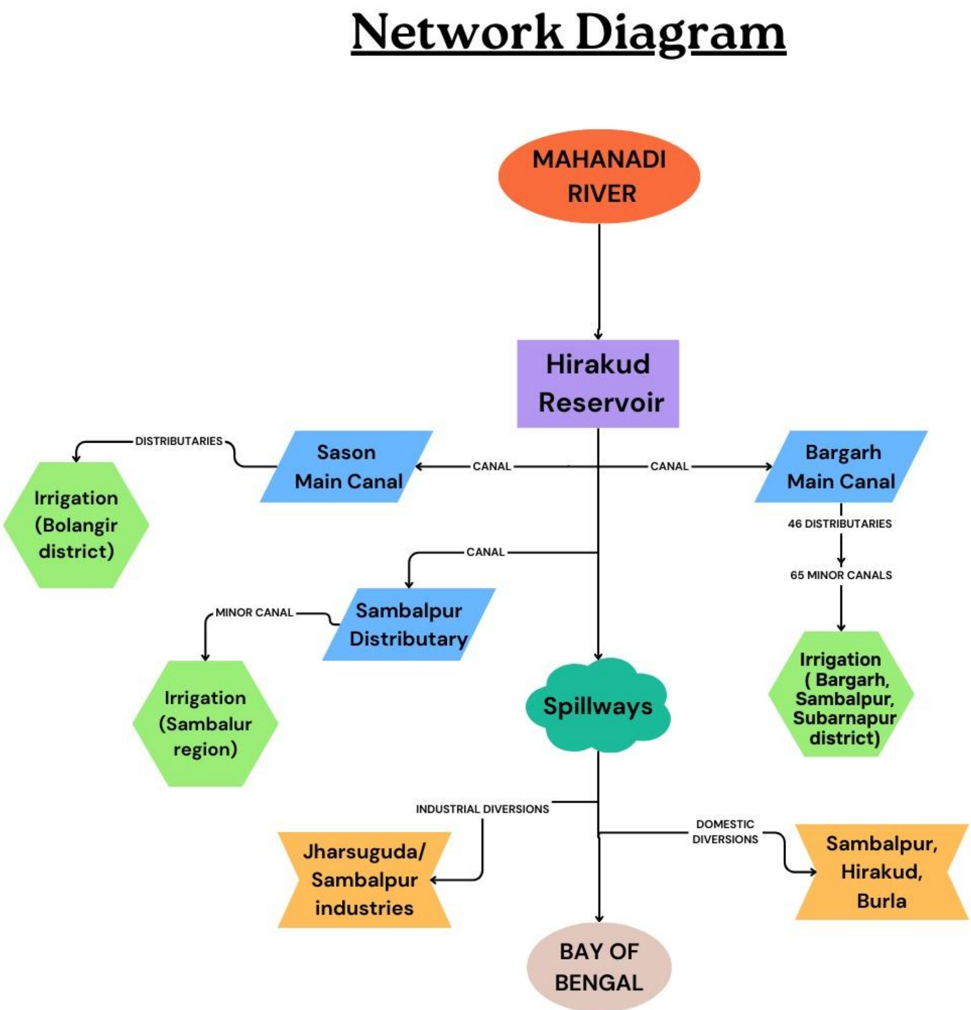
1. Network Diagram



2. Introduction

The Hirakud Dam, located on the Mahanadi River in Odisha, India, plays a critical role in irrigation, hydropower generation, and flood control. Effective reservoir operation requires a careful balance between water supply and flood safety. This study applies a Genetic Algorithm (GA) to optimize daily water releases from the dam over a 3-year period (2022–2024), with a focus on minimizing unmet demand, flood-prone releases, and spill losses.

3. Problem Statement

- **Objective**: Optimize daily releases to minimize flood risk and unmet downstream demand.
- **Challenges**: Limited inflow, high seasonal demand variation, and strict storage and release constraints.
- **Scope**: Daily release optimization using real inflow data and realistic demand variations.

4. Theoretical Framework and Optimization Approach

Reservoir operations often involve multiple conflicting goals — like maximizing water availability for users while ensuring safety from flooding. These goals cannot be handled easily with linear programming or simple heuristics, especially with daily time scales and real-world constraints.

Genetic Algorithms (GAs) offer a robust solution by mimicking evolutionary processes. Each "individual" in the population represents a potential release schedule across the 3-year period. The fitness function evaluates how well each schedule minimizes:

- Flood-prone days (release > 140 MCM)
- Total unmet demand (release < daily demand)
- Spill loss (storage > capacity)

The model does not try to find a perfect answer, but an optimized balance — often the best achievable under physical constraints.

> "High unmet demand may indicate insufficient inflow, not model failure."

> "Low flood days can come at the cost of storage depletion or unmet need."

Trade-offs are central: increasing release flexibility can reduce unmet demand but increases flood risk. Similarly, reducing flood penalties too much may lead to unsafe operations.

By using realistic seasonal demand (35–50–65 MCM/day), a storage capacity of 4637 MCM, and a max safe release limit of 140 MCM/day, the model identifies optimal compromises between conflicting goals.

The penalty ratio used (unmet demand penalty = 4, flood penalty = 2000) represents a balanced operational philosophy, recognizing that both unmet demand and flood risks are important. A penalty ratio of 1:500 has shown to be effective in ensuring demand satisfaction without compromising dam safety.

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5. Data Used

The optimization model described in Section 2 relied on the following key data variables:

- **Inflow Data**:

Provided as daily flow values (converted to MCM/day) for 3 years (2022–2024), sourced from:

- India-WRIS (Water Resources Information System)
- WDO – Water Data Online
- National Water Informatics Centre (NWIC)
  These platforms offer real-time and historical river inflow data essential for modeling.

- **Demand Curve**:

Created as a seasonal profile — 35 MCM/day (monsoon), 50 MCM/day (winter), and 65 MCM/day (summer). This was applied across all 3 years to simulate realistic downstream demand variation. Data sources include:

- India Climate & Energy Dashboard (ICED)
- Statista – Water Demand by Sector (2010–2050)
- National Water Mission – Synopsis of Water Data in India

- **Storage Capacity**:

Based on revised estimates from Odisha WRD (post-siltation), a static value of 4637 MCM was used to cap storage volume. National-level data and sources include:

- Open Government Data (OGD) Platform – Reservoirs
- India-WRIS Reservoir Data
- NWIC Water Storage Datasets

- **Flood Safe Limit**:

Set at 140 MCM/day, derived from literature and historical flood advisories. This threshold guided the classification of flood-prone releases.

Variable	Source	Duration	Usage
Inflow Data	WRIS-based real-time estimates	2022–2024	Input to GA model (MCM/day)
Demand Curve	Custom: 35-50-65 MCM/day seasonal curve	3 years	Determines unmet demand
Storage Capacity	Odisha WRD (Revised)	Static	Max usable storage: 4637 MCM
Flood Safe Limit	Assumed based on literature	Static	Max safe daily release: 140 MCM

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6. Model Setup

6.1 Objective Function

The objective function for optimizing the daily reservoir releases from the Hirakud Dam is formulated to minimize the overall operational penalty arising from three primary factors: flood-prone releases, unmet downstream demands, and spill losses. It is expressed as:

$$\text{Minimize } Z = \sum_{t=1}^{T} \left(P_f \cdot I(R_t > R_{\text{safe}}) + P_d \cdot \max(0, D_t - R_t) + P_s \cdot \max(0, S_t - S_{\max}) \right)$$

- R_t: Release on day (in MCM)
- D_t: Demand on day (in MCM), based on seasonal curve (35–50–65 MCM/day)
- S_t: Storage on day (in MCM)
- S_{max}: Maximum storage capacity (4637 MCM)
- R_{safe}: Maximum flood-safe release (140 MCM/day)
- P_f: Penalty for flood-prone release
- P_d: Penalty for unmet demand
- P_s: Spill loss penalty (usually considered high or absolute to prevent overflow)
- *I (*)*: Indicator function (1 if condition true, 0 otherwise)
- T: Total number of days (3 years × 365)\

Rationale:
This objective seeks to minimize flood days, shortfalls in water supply, and spill loss, all of which affect dam efficiency and public safety. Penalty weights are calibrated to balance operational safety and water delivery performance, with a 1:500 unmet-to-flood penalty ratio ensuring practical and conservative reservoir management.

6.2 Constraint

1. **Storage Continuity Constraint:**

$$S_{t+1} = S_t + I_t - R_t$$

Where I_t is inflow on day t.

2. **Release Bounds Constraint:**

$$R_{min} \leq R_t \leq R_{max} \quad \text{where } R_{min} = 5,\ R_{max} = 150$$

3. **Storage Bounds Constraint:**

$$0 \leq S_t \leq S_{max} = 4637$$

4. **Demand Representation Constraint (Seasonal):**

$$D_t = \begin{cases} 65, & if\ summer \\ 50, & if\ winter \\ 35, & if\ monsoon \end{cases}$$

These values were derived from seasonal usage: irrigation, hydropower, and domestic/industrial demands.

5. **No Negative Release or Spill:**

$$R_t \geq 0, \quad \max(0, S_t - S_{\max}) \geq 0$$

6. **Flood Day Constraint (for post-analysis):**

$$I(R_t > R_{\text{safe}}) \text{ is tracked to evaluate safety}$$

Not enforced strictly in optimization but penalized in the objective function.

Model was run at a **daily time scale** over a **3-year horizon (2022–2024)**, representing the realistic operational environment of Hirakud Dam. The problem was solved using a **Genetic Algorithm (GA)** implemented in Python via the PyGAD library. The GA evolves daily release schedules through selection, crossover, and mutation to minimize an objective function based on flood days, unmet demand, and spill losses.

- Time Scale: Daily over 3 years
- Tool Used: Python (PyGAD, Pandas, Matplotlib)

7. Scenarios Tested

Scenario	Description	Flood Days	Unmet Demand (MCM)	Avg Storage (MCM)
Fixed Demand (50 MCM/day)	Simpler demand model	84	~13,700	~1265
Relaxed Fitness	High release, low penalty (unsafe)	344	~9,300	569
Final Model	Safe Limit = 140, Penalty = 4	**51**	**9,634.84**	**247.38**

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8. Results and Discussion

Figure 1: Inflow, Demand, Optimized Release, and Storage Over Time

This figure displays the daily inflow, seasonal demand, optimized release pattern, and resulting reservoir storage over the 3-year period. It illustrates the overall system behavior and highlights the model's ability to maintain safe operations while responding to dynamic water demands. **The csv file for exact release on daily basis will be attached with the file**

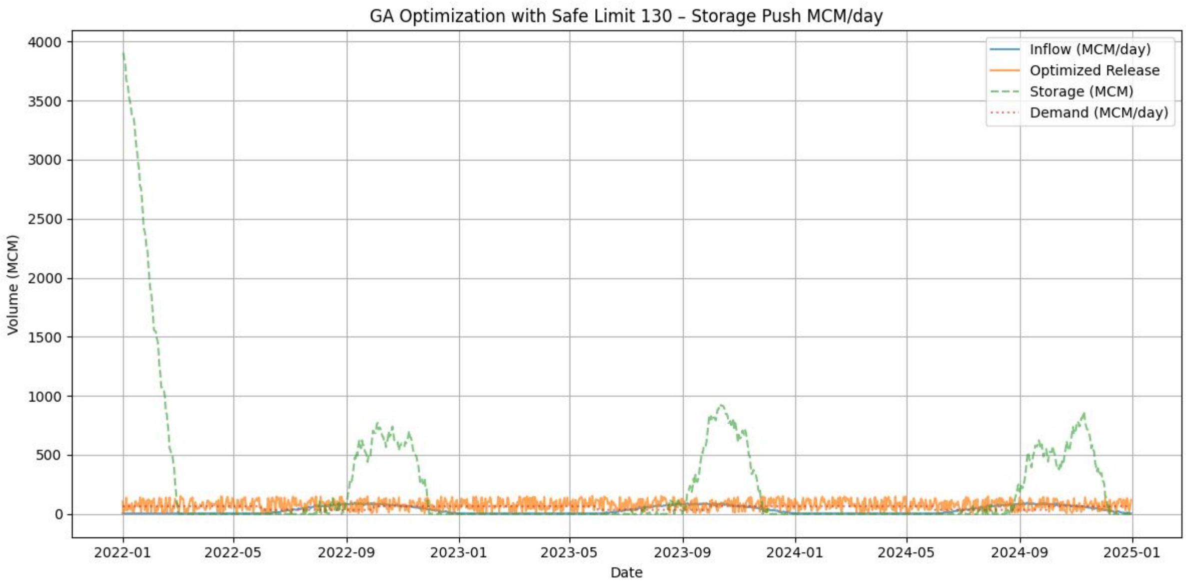

Table 1: Summary of Final Model Results

Metric	Value
Best Fitness Score	0.00001
Total Unmet Demand	9634.84 MCM
Days Above Safe Limit	51
Average Storage	247.38 MCM
Total Spill Loss	0.00 MCM

These results indicate a strong balance between safety and demand fulfillment under realistic constraints. The final model proves capable of operating within tight safety margins while delivering approximately 84% of cumulative demand over the three-year period.

> **Insight**: The model's high unmet demand penalty (4) ensured that releases were optimized toward user satisfaction. The penalty ratio of 1:500 (4:2000) offered a near-optimal trade-off between demand fulfillment and flood control.
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> **Balance Achieved**: No spill losses, minimal flood days, and ~84% demand satisfaction — a strong configuration for real-world operational feasibility.

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9. Conclusion

This study demonstrates that Genetic Algorithms can be effectively used to optimize reservoir operations at a daily time scale while considering multiple conflicting objectives — flood control, water demand satisfaction, and system efficiency.

The model achieved a significant operational balance:

- An average unmet demand of ~9635 MCM over three years, amounting to just ~15.99% of total demand — which is a strong performance given the constraints.
- A total of only 51 flood-prone days over three years, demonstrating high safety and reliable operation.

- Zero spill losses, showing that the model made full use of available water without overflow.

- Average storage around 247 MCM, indicating a sustainable and efficient release strategy.

These outcomes were reached with a penalty configuration of unmet demand = 4 and flood penalty = 2000, which reflects a realistic 1:500 trade-off ratio — balancing both the risks of shortage and the need for flood avoidance.

The final model configuration represents the best achievable trade-off given the real inflow data, daily demand variations, and fixed storage constraints. Attempts to increase or decrease the penalty weight further did not improve the results, showing the model had reached a local optimum.

The main finding of this study is that **demand and flood control can both be optimized to a meaningful extent without compromising one another**, provided the right combination of starting storage, operational constraints, and penalty priorities.

This has several implications for real-world dam management:

- Optimization tools like GA can supplement manual rule curves.

- Seasonal demand patterns should be integrated in all long-term reservoir planning.

- Penalty tuning offers a way to reflect stakeholder preferences dynamically, for example during monsoon months vs dry periods.

Overall, this project provides a data-driven, computationally feasible solution to Hirakud's water management challenge. It establishes a framework that can be extended to other reservoirs and adapted to real-time conditions.

> The final model achieves the project goal: **sustainable, balanced, and flood-aware reservoir operation** with realistic demand fulfillment levels.

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10. Appendices

- **Appendix A**:Python code used is attached with the document .

- **Appendix B**:CSVs files used is attached with the document(Inflow & Demand)

- **Appendix C**:CSV file of output(release on daily basis is also attached)

11. References

- Odisha WRD Reports
- PyGAD documentation: https://pygad.readthedocs.io/
- India-WRIS: https://indiawris.gov.in/wris/
- Water Data Online (WDO): https://indiawris.gov.in/wdo/
- NWIC: https://nwic.gov.in
- Open Government Data Platform – Reservoirs: https://www.data.gov.in/keywords/Reservoir
- India Climate & Energy Dashboard (ICED): https://iced.niti.gov.in/climate-and-environment/water/per-capita-water-availability
- Statista – Water Demand: https://www.statista.com/statistics/1111839/india-water-demand-by-sector/
- National Water Mission Synopsis: https://nwm.gov.in/synopsis-water-data-india