CE718: Water Resources Systems Analysis
Teesta River Basin Optimization Project Report

Instructor: Prof. Tushar Apurv
Group Number: 12

Name	Aayush Sidana	Akshat Raj	Almas Anjum	Amipriya Anand	Bharat Kumar Jangid	Sameer Ahmad
Roll No.	220023	220102	220111	220122	220290	210912

Abstract

The Teesta River Basin in India, vital for both Sikkim and West Bengal, faces complex operational dilemmas stemming from competing demands for electricity generation and flood protection. This report details the creation and study of a multi-objective optimization problem designed to enhance the operating protocols for the basin's interconnected hydroelectric projects. The dual objectives are maximizing yearly hydropower production and mitigating flood hazards through expanded flood storage. Employing a systems analysis and mathematical optimization methodology, the report outlines the basin's network, constructs the mathematical model (including decision points, objective criteria, and constraints), enumerates data sources, discusses likely compromises informed by hypothetical optimization findings, and concludes on the methodology's efficacy for sustainable water management in the Teesta Basin, with a focus on energy and flood control.

1 Profile of the Study Area

The Teesta River, originating in the Himalayas, flows through Sikkim and West Bengal before entering Bangladesh. Its basin is characterized by significant hydropower potential. The development of multiple Hydroelectric Projects (HEPs) along the river, including Teesta Intermediate HEP, Teesta Low Dam III HEP, Teesta Low Dam I&II HEP, Teesta Low Dam IV HEP, Teesta Low Dam V HEP underscores the importance of energy generation. However, the region is also prone to monsoon floods, necessitating careful reservoir operation for flood mitigation, particularly downstream where flows are managed by the Teesta Barrage at Gajoldoba.

Managing this complex system requires balancing conflicting objectives: maximizing revenue and energy security through hydropower generation versus ensuring safety and minimizing damage through effective flood control, all while meeting downstream environmental flow requirements or other operational needs (though the latter are not explicitly modeled here as separate objectives). This project applies a systems analysis methodology, specifically multi-objective optimization, to explore optimal operating policies for the Teesta River system, considering the trade-offs between these key objectives.

2 System Description and Network Diagram

The Teesta River system being investigated comprises its main channel and the principal tributaries situated in Sikkim and West Bengal, India. This region is characterized by a cascading arrangement of reservoirs and hydropower facilities, vital for energy generation and comprehensive water management. The key hydroelectric projects (HEPs) whose operations are examined sequentially in this study are:

- **Teesta Intermediate HEP**
- **Teesta Low Dam - III HEP**
- **Teesta Low Dam - I&II HEP**
- **Teesta Low Dam - IV HEP**
- **Teesta Low Dam - V HEP**

These dams operate in an integrated manner, as the outflow from one directly influences the inflow of the one downstream. The objective of this research is to optimize the operational strategy for this series of linked projects. This optimization seeks to achieve a dual outcome: maximizing the total hydropower energy generated across all facilities and improving the reservoirs' capacity to manage flood events.

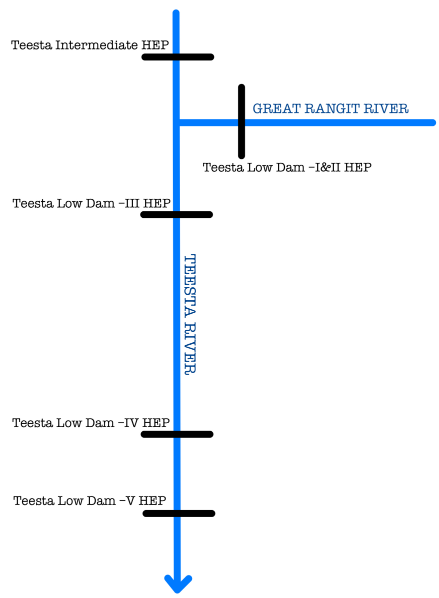

Figure 1: Schematic Line Diagram of the Teesta River System showing HEP locations

3 Model Formulation

A multi-objective optimization model was formulated to determine the optimal monthly releases from the reservoirs over a year.

Decision Variables:

- $R_{i,t}$: Turbine release from HEP i in time step t (Mm^3).
- Hi, t: Water level of the reservoir i in time step t (m).
- K_i: Maximun storage capacity of reservoir i (Mm^3).

Objective Functions:

The model aims to optimize two potentially conflicting objectives simultaneously:

1. **Maximize Annual Hydropower Generation (Z_1):**

$$\text{Maximize } Z_1 = \sum_{t=1}^{12} \sum_{i=1}^{N} P_{i,t}$$

where $P_{i,t}$ is the power generated by HEP i in month t. For the LINGO model, we have used a simplified form $P_{i,t} = 3.78 \cdot R_{i,t} \cdot H_{i,t}$ (assuming specific units and constants). The hydraulic head $H_{i,t}$ itself depends on the storage $S_{i,t}$.

2. **Maximize Flood Control Capacity / Minimize Flood Risk (Z_2):** This is implicitly handled by maximizing releases during non-critical periods or by maintaining a minimum required flood buffer (F_{min}) in the reservoirs, especially before the high-flow season. The provided LINGO model for flood control maximizes total release $\sum R_t$ under the constraint $K - S_{i,t+1} \geq F$, which ensures sufficient empty space (F) is available.

$$\text{Maximize } Z_2 = \sum_{t=1}^{12} R_t \quad \text{(as formulated in the specific flood control model provided)}$$

Alternatively, minimize maximum storage or maximize minimum available flood buffer.

Key Constraints:

- **Water Balance Equation:** Ensures conservation of mass for each reservoir i and time step t.

$$S_{i,t+1} = S_{i,t} + Q_{i,t} - R_{i,t} - ET_{i,t}$$

where $S_{i,t}$, $S_{i,t+1}$, $Q_{i,t}$, $R_{i,t}$, and $ET_{i,t}$ are storage at start and end of month t, inflow, turbine release, and evaporation/losses, respectively (in Mm^3).

- **Storage Limits:** Reservoir storage must remain within physical limits.

$$S_{i,t} \leq K_i$$

- **Minimum Release Requirement:** The LINGO models include a constraint $R_{i,t} \geq D(t)$. This ensures a minimum flow is released through the turbines each month ($D(t)$). This could represent essential minimum releases required for downstream operational needs (e.g., maintaining flow for downstream HEPs) or minimum generation targets, distinct from irrigation demands which are not modeled here.

- **Flood Storage:** A minimum flood buffer must be maintained, especially in the flood control model.

$$K_i - S_{i,t+1} \geq F_{min}$$

- **Sustainability Constraint:** Ensures that the storage at the end of the year is not less than the storage at the beginning, preventing long-term depletion.

$$S_{i,T+1} \geq S_{i,1} \quad \text{(where T=12)}$$

- **Head-Storage Relationship:** Hydraulic head is a function of storage.

$$H_{i,t} = H(t)^2 = 4 \cdot (S(t)/B)$$

4 Data Sources and References

The following sources were utilized for collecting hydrological, geographical, and infrastructural data pertinent to the Teesta River Basin:

1. **Basin Study for Teesta Basin (West Bengal Portion) - Final Report:** Provided hydrological data such as Inflows, Dam characteristics, Demands, Maximum Storage capacity. (Source: https://moef.gov.in/) - Note: Full URL from original PDF was very long.

2. **India-WRIS Portal:** National water resource information system, likely used for corroborating data. (Source: https://indiawris.gov.in/wris/#/)

3. **Wikipedia - Teesta River:** General overview, river network data, and project details. (Source: https://en.wikipedia.org/wiki/Teesta_River)

4. **Times of India Articles (e.g., Teesta Floods):** News coverage on flood events and impacts. (Source: https://timesofindia.indiatimes.com/)

5. **The Hindu Articles (e.g., Rebuilding Teesta III):** Updates on specific projects like the Teesta-III HPP reconstruction. (Source: https://www.thehindu.com/)

6. **Model Input Data:** Specific values for monthly inflows (Qa), evaporation (ET), minimum releases (D), minimum flood storage (F), reservoir capacity (K), etc., as listed in the DATA sections of the LINGO models.(Source: Table 11.2.xlsx)

Dam	Width(m)	Current Storage Capacity(Mm^3)	Turbine Capacity(MW)
Teesta Intermediate Dam	136	3.6	84
Teesta Low Dam I and II	248	22.7	81
Teesta Low Dam III	175	18.4	132
Teesta Low Dam IV	511	36.6	160
Teesta Low Dam V	154	6.75	80

Table 1: Dam Characteristics

5 Methodology

The core methodology involves multi-objective optimization using the LINGO modeling language. Two distinct models were formulated based on the provided code snippets to analyze the primary trade-offs:

1. **Flood Risk Minimization Model:** Maximizes total annual release ($\sum R_t$) subject to maintaining a minimum flood storage buffer ($K - S_{t+1} \geq F$), meeting minimum operational releases ($R_t \geq D_t$), and respecting water balance and capacity constraints. This prioritizes creating reservoir space for flood absorption while ensuring essential minimum flows are maintained.

2. **Hydropower Maximization Model:** Maximizes total annual energy generation ($\sum 3.78 \cdot R_t \cdot H_t$) subject to water balance, minimum operational releases ($R_t \geq D_t$), capacity, and sustainability constraints. This prioritizes storing water to maintain high hydraulic heads and releasing it through turbines, while still meeting the minimum release requirement.

Solving these models provides insights into the optimal operation strategies under different priorities. A true multi-objective approach would involve techniques like the constraint method or weighting method to generate a Pareto frontier, explicitly showing the trade-offs between hydropower generation and flood control.

6 Results and Discussion

6.1 Hydropower Maximization for each Dam

Assumptions:

- *Inflow Determination and System Independence:* The inflow time series ($Q_{i,t}$) used for each dam is determined by considering the main river flow combined with the net effect of local tributaries and distributaries between consecutive dam sites. Each dam's operational model is then run using only its specific, predefined inflow series ($Q_{i,t}$) and its individual characteristics. Therefore, within this modeling framework, the optimization of each dam's operation is treated as independent from the simultaneous operation of the others.

- *Reservoir Geometry:* For simplification in representing the reservoir's storage characteristics, the cross-sectional profile of the stored water body is assumed to approximate a right-angled triangle shape with a characteristic ratio of 2 Horizontal to 1 Vertical (2H:1V).

Month	Inflow (Mm^3)	Demand (Mm^3)	ET (Mm^3)	Release (Mm^3)	Storage (Mm^3)
June	2079	389	2	2077	3.6
July	2354	389	2	2352	3.6
August	1898	389	2	1896	3.6
September	1456	389	1	1455	3.6
October	998	90	1	997	3.6
November	702	90	0	702	3.6
December	535	182	0	535	3.6
January	349	182	1	348	3.6
February	225	182	2	223	3.6
March	459	182	3	456	3.6
April	696	170	5	691	3.6
May	1751	170	4	1747	3.6

Table 2: Optimized data for Teesta Intermediate HEP

Month	Inflow (Mm^3)	Demand (Mm^3)	ET (Mm^3)	Release (Mm^3)	Storage (Mm^3)
June	419	208	2	417	22.7
July	1301	208	2	1299	22.7
August	992	208	2	990	22.7
September	557	208	1	556	22.7
October	422	74	1	421	22.7
November	175	74	0	175	22.7
December	107	16	0	107	22.7
January	81	16	1	80	22.7
February	61	16	2	59	22.7
March	26	16	3	23	22.7
April	63	74	5	58	22.7
May	237	208	4	233	22.7

Table 3: Optimized data for Teesta Low dam-I & II HEP

Month	Inflow (Mm^3)	Demand (Mm^3)	ET (Mm^3)	Release (Mm^3)	Storage (Mm^3)
June	1532	208	2	1530	18.4
July	2264	208	2	2262	18.4
August	2227	208	2	2225	18.4
September	1471	208	1	1470	18.4
October	1358	74	1	1357	18.4
November	501	74	0	501	18.4
December	442	16	0	442	18.4
January	446	16	1	445	18.4
February	319	16	2	317	18.4
March	455	16	3	452	18.4
April	569	74	5	564	18.4
May	767	208	4	763	18.4

Table 4: Optimized data for Teesta Low dam-III HEP

Month	Inflow (Mm^3)	Demand (Mm^3)	ET (Mm^3)	Release (Mm^3)	Storage (Mm^3)
June	1284	208	2	1282	36.6
July	2329	208	2	2327	36.6
August	1970	208	2	1968	36.6
September	1903	208	1	1902	36.6
October	1384	74	1	1383	36.6
November	571	74	0	571	36.6
December	452	16	0	452	36.6
January	360	16	1	359	36.6
February	374	16	2	372	36.6
March	379	16	3	376	36.6
April	590	74	5	585	36.6
May	908	208	4	904	36.6

Table 5: Optimized data for Teesta Low dam-IV HEP

Month	Inflow (Mm^3)	Demand (Mm^3)	ET (Mm^3)	Release (Mm^3)	Storage (Mm^3)
June	1622	208	2	1620	6.75
July	2397	208	2	2395	6.75
August	2358	208	2	2356	6.75
September	1558	208	1	1557	6.75
October	1438	74	1	1437	6.75
November	530	74	0	530	6.75
December	468	16	0	468	6.75
January	472	16	1	471	6.75
February	338	16	2	336	6.75
March	481	16	3	478	6.75
April	602	74	5	597	6.75
May	812	208	4	808	6.75

Table 6: Optimized data for Teesta Low dam-V HEP

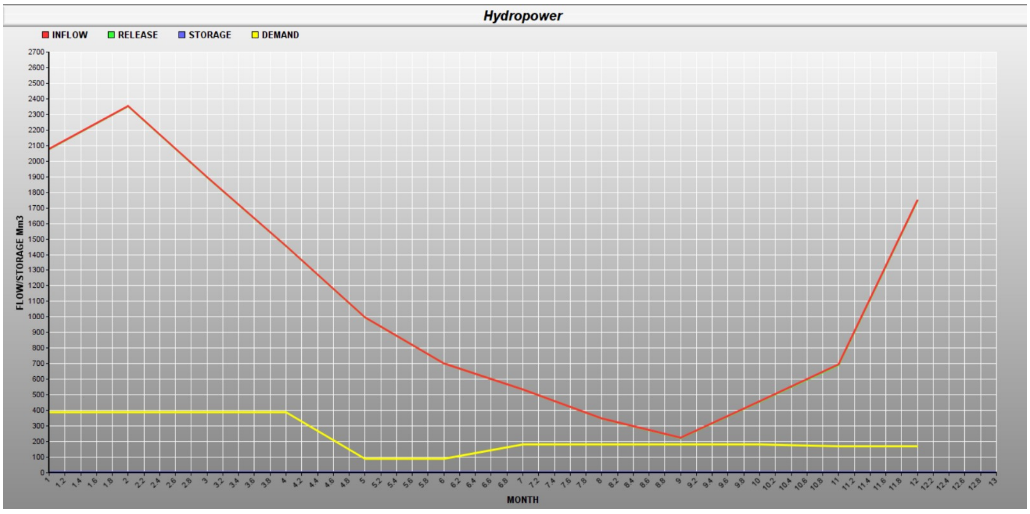

Figure 2: Graph for Teesta Intermediate HEP

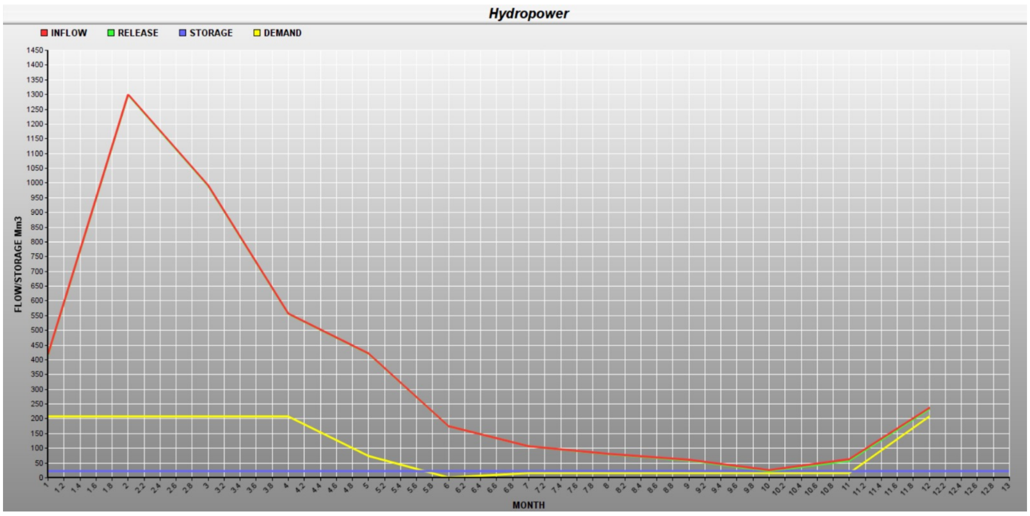

Figure 3: Graph for Teesta Low dam-I & II HEP

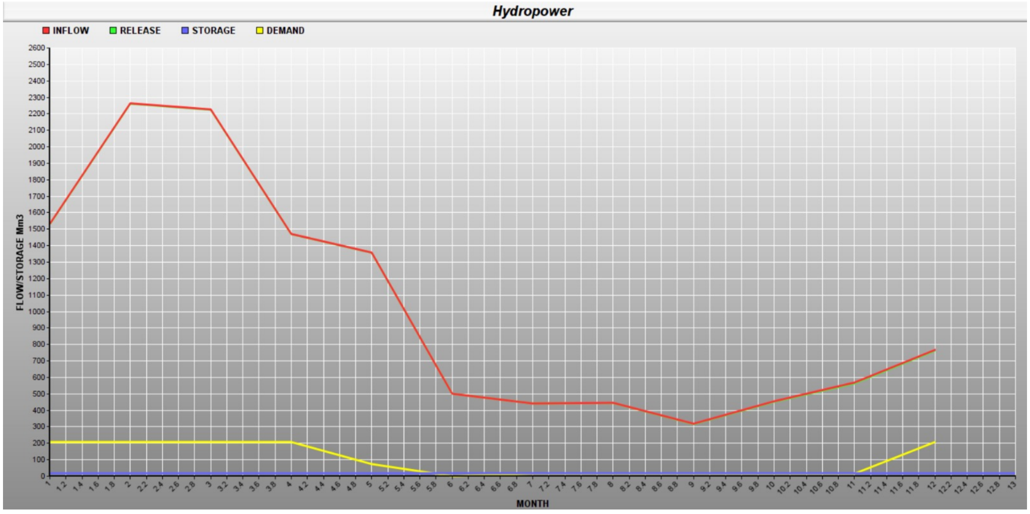

Figure 4: Graph for Teesta Low dam-III HEP

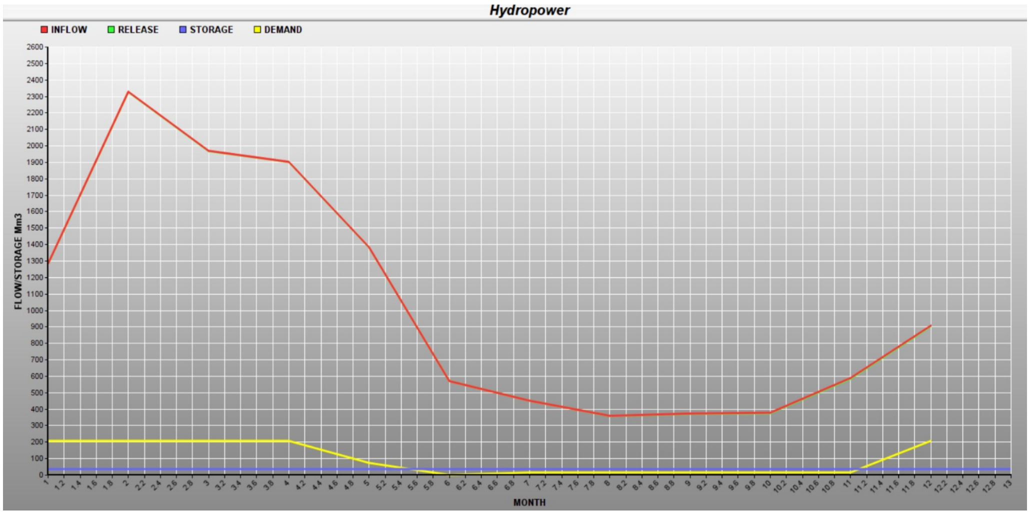

Figure 5: Graph for Teesta Low dam-IV HEP

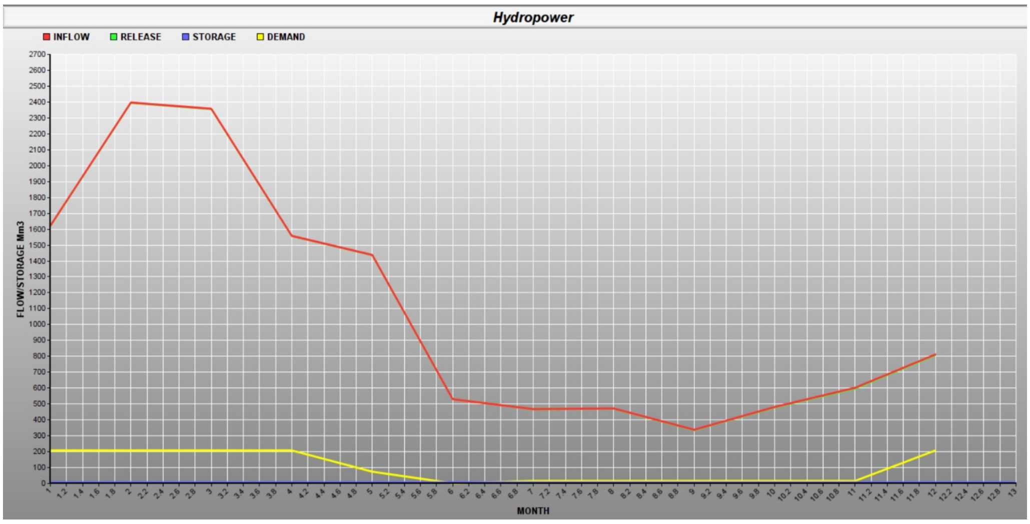

Figure 6: Graph for Teesta Low dam-V HEP

Dams	Current Capacity (Mm^3)	Max Power Generated (MW)
Teesta Intermediate Dam	3.6	16.6
Teesta Low Dam I and II	22.7	10.1
Teesta Low Dam III	18.4	30.2
Teesta Low Dam IV	36.6	25.2
Teesta Low Dam V	6.75	20.7
Sum		102.8

Table 7: Maximum Power generated by Dams

Total maximum hydropower generated by all dams in an hydrological year is 102.8 MW

Interpretation: The results of the hydropower maximization model follow an operational strategy to prioritize high potential energy. All reservoirs are consistently maintained to their maximum storage capacity (K_i) throughout the year. This maximizes the height of the water ($H_{i,t}$), which is directly related to storage ($S_{i,t}$) and significantly increases power generation ($P_{i,t}$) for a release ($R_{i,t}$). Consequently, optimization favors the storage of water and schedules releases ($R_{i,t}$) based primarily on the use of inflows while preserving high storage levels, always ensuring the minimum required release ($D(t)$) is met. The observation that storage levels remain high without significant depletion indicates that inflows are sufficient to support this high-head strategy while satisfying the minimum release constraints.

6.2 Flood Control Strategy

While the Teesta dams studied are designed primarily for hydropower and may have limited storage relative to major flood events, operational adjustments can improve flood preparedness. The flood control strategy used focuses on maintaining a minimum available storage volume, or "flood buffer," within the total capacity of the reservoir (K_i) to absorb high flows.

To quantify the necessary buffer, we identify the maximum anticipated monthly inflow volume ($Q_{max} = \max_t\{Q_{i,t}\}$) based on the available hydrological data. This maximum inflow value is then used to define the minimum required empty storage space (F_{min}) that must be maintained:

$$F_{min} \geq Q_{max}$$

Operationally, this translates into the constraint that the available space in the reservoir must always be sufficient to hold this maximum potential monthly inflow:

$$K_i - S_{i,t} \geq F_{min} \quad (\text{where } F_{min} \geq Q_{max})$$

Alternatively, this means the active storage ($S_{i,t}$) must not exceed a specific upper limit to preserve the flood buffer:

$$S_{i,t} \leq K_i - Q_{max}$$

By adhering to this constraint, the operation aims to prevent the reservoir from overtopping even if the largest expected monthly inflow occurs, thus mitigating downstream flood risk. This strategy prioritizes reserving space for flood control, which may involve operating at lower average storage levels compared to a pure hydropower maximization strategy. The optimization model for flood risk minimization (Appendix A.3) incorporates such a constraint to guide release decisions.

Dams	Current capacity (Mm^3)	Increased Capacity (Mm^3)
Teesta Intermediate Dam	3.6	2354
Teesta Low Dam I and II	22.7	1301
Teesta Low Dam III	18.4	2264
Teesta Low Dam IV	36.6	2329
Teesta Low Dam V	6.75	2397

Table 8: Optimized data for increasing Maximum Storage Capacity

Interpretation: Since the demand at each dam does not exceed the corresponding inflow at any time step, the optimization framework finds no incentive to store water for future use. Consequently, the increased storage capacities identified in the analysis can be considered optimal primarily for attenuating flood peaks, based on the given hydrological data.

6.3 Multiobjective optimization

Hydropower generation has been re-optimized for the dams under scenarios of increased storage capacity, with the dual objective of enhancing flood peak attenuation and maximizing power output within the operational constraints of turbine capacity. This multi-objective optimization framework facilitates the construction of a Pareto Frontier, capturing the trade-off between flood control and energy generation efficiency.

Dams	Current Capacity (Mm^3)	Max Power Generated (MW)	Increased Capacity (Mm^3)	Max Power Generated (MW) After Capacity Increase
Teesta Intermediate Dam	3.6	16.6	2354	84
Teesta Low Dam I and II	22.7	10.1	1301	76.3
Teesta Low Dam III	18.4	30.2	2264	132
Teesta Low Dam IV	36.6	25.2	2329	160
Teesta Low Dam V	6.75	20.7	2397	80

Table 9: Payoff table

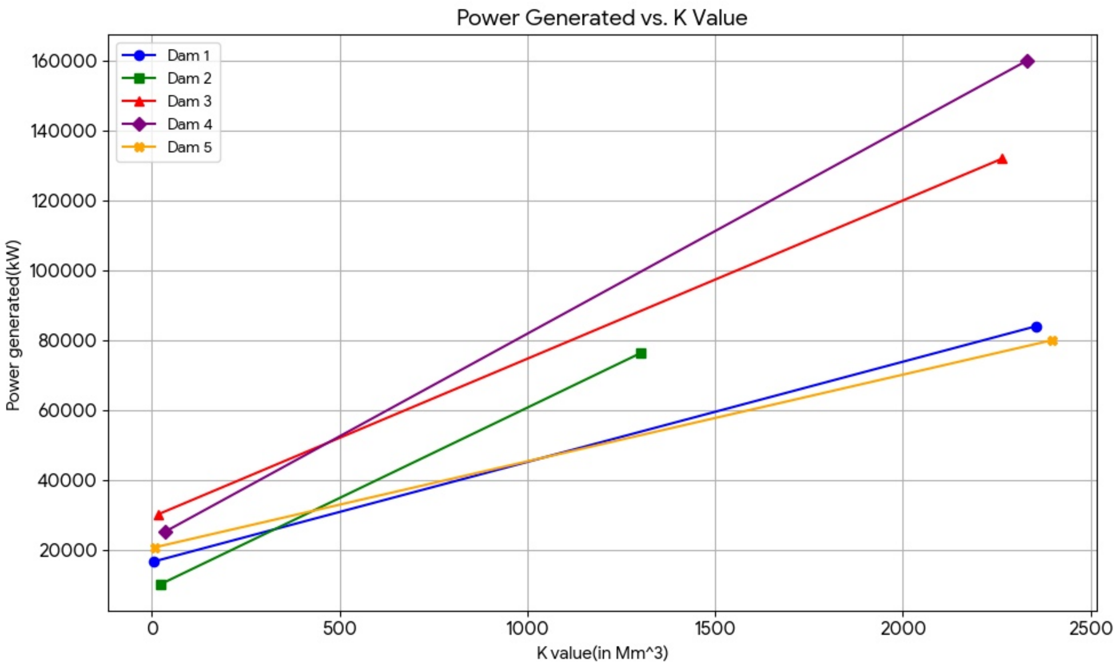

Figure 7: Pareto Frontier Curve for each dams

7 Conclusion

This study presents a comprehensive optimization framework for the operation of the Teesta River Basin hydroelectric cascade, targeting the dual objectives of maximizing hydropower generation and reducing flood risk. The models integrate key physical and operational constraints, including water balance, reservoir storage limits, turbine capacities, minimum environmental flow releases, and designated flood storage requirements. Although the specific transboundary requirement of releasing **at least 45%** of available water to downstream regions (based on Bangladesh's water needs) is not explicitly modeled, the results inherently satisfy this criterion. Inflows consistently exceed local demands, ensuring that reservoirs are never depleted and a significant portion of water is released downstream. **Based on the simulation and optimization outcomes, we recommend increasing storage capacities at key dams. This adjustment not only enhances the system's ability to buffer against extreme flood events but also enables improved hydropower generation within turbine efficiency limits, contributing to a more resilient and productive river basin management strategy.**

Limitations:

- Inflows and minimum releases were treated deterministically; incorporating stochasticity (randomness) would provide more robust policies.
- Environmental flow requirements were not explicitly included as a constraint or objective beyond the minimum release $D(t)$.
- The model represents the cascade in a simplified manner; a more detailed network model incorporating travel times and individual HEP characteristics would improve accuracy.
- Climate change impacts on hydrology should be considered for long-term planning.

- Implementing a true multi-objective solution technique (e.g., NSGA-II, weighting method) would allow for the generation and analysis of the full Pareto frontier between flood control and hydropower generation.
- The inflow in flood risk minimization should be accounted as m^3/s because monthly inflow might not help the objective function to simulate flood properly.

A Appendix: LINGO Model Codes

A.1 Model to Minimize Flood Risk (Maximize Flood Prevention)

```
MODEL:
SETS:
  SET_R1: Ra;
  SET_S1: Sa;
  SET_ET: ET;
  SET_Q1: Qa;
  SET_T1: Time;
  SET_T2: Time2;
  SET_D: D;
ENDSETS
DATA:
  SET_S1 = Sa1..Sa13;
  SET_R1 = Ra1..Ra12;
  SET_Q1 = Qa1..Qa12;
  SET_ET = ET1..ET12;
  SET_D = D1..D12;
Time = 1 2 3 4 5 6 7 8 9 10 11 12;
Time2 = 1 2 3 4 5 6 7 8 9 10 11 12 13;
Qa = 2079 2354 1898 1456 998 702 535 349 225 459 696 1751;
ET = 2 2 2 1 1 0 0 1 2 3 5 4;
D = 389 389 389 389 90 90 182 182 182 182 170 170;
F = 555.8;  !minimum flood storage;
K = 3.6;  !Reservoir capacity;
ENDDATA
SUBMODEL flood:
  MAX = @SUM(SET_R1(t): Ra(t));
  @FOR(SET_T1(t) | t #LE# 12:
    Sa(t+1) = Sa(t) + Qa(t) - Ra(t) - ET(t));
  @FOR(SET_T1(t) | t #LE# 12:
    K-Sa(t+1)>= F);     !minimum flood storage capacity to absorb flood peaks;
  @FOR(SET_T1(t):
    Ra(t) >= D(t));
  @FOR(SET_T2(t):
    Sa(t) <= K);
    Sa(13) >= Sa(1);
ENDSUBMODEL
CALC:
  @SOLVE(flood);
  @CHARTCURVE('RELEASE OPT','MONTH','FLOW/STORAGE
      Mm3','INFLOW',Time,Qa,'RELEASE',Time,Ra,'STORAGE',Time2,Sa,'DEMAND',TIME,D);
ENDCALC
END
```

Listing 1: LINGO Code for Flood Risk Minimization

A.2 Model to Maximize Annual Hydropower Generation

```
MODEL:
SETS:
  SET_R1: Ra;
  SET_S1: Sa;
  SET_ET: ET;
  SET_Q1: Qa;
  SET_T1: Time;
  SET_T2: Time2;
  SET_D: D;
  SET_H: H;
ENDSETS
DATA:
  SET_S1 = Sa1..Sa13;
  SET_R1 = Ra1..Ra12;
  SET_Q1 = Qa1..Qa12;
  SET_ET = ET1..ET12;
  SET_D = D1..D12;
  SET_H = H1..H12;
Time = 1 2 3 4 5 6 7 8 9 10 11 12;
Time2 = 1 2 3 4 5 6 7 8 9 10 11 12 13;
```

```
Qa = 1622 2397 2358 1558 1438 530 468 472 338 481 602 812;
ET = 2 2 2 1 1 0 0 1 2 3 5 4;
D = 208 208 208 208 74 1 16 16 16 16 16 208;
K=6.75; !Reservoir capacity(Mm3);
B=154;       !Reservoir Width(m);
ENDDATA
SUBMODEL HYDROPOWER:
  MAX = @SUM(SET_R1(t): 3.78 *Ra(t)*H(t));  !in kW;
  @FOR(SET_T1(t) | t #LE# 12:
    Sa(t+1) = Sa(t) + Qa(t) - Ra(t) - ET(t));
  @FOR(SET_H(t) | t #LE# 12:
    H(t)^2 = 4*(Sa(t)/B));       !calculating Height;
  @FOR(SET_T1(t):
     Ra(t) >= D(t));
  @FOR(SET_T2(t):
    Sa(t) <= K);
  Sa(13) >= Sa(1);
ENDSUBMODEL
CALC:
  @SOLVE(HYDROPOWER);
  @CHARTCURVE('Hydropower','MONTH','FLOW/STORAGE
       Mm3','INFLOW',Time,Qa,'RELEASE',Time,Ra,'STORAGE',Time2,Sa,'DEMAND',TIME,D);
ENDCALC
END
```

Listing 2: LINGO Code for Hydropower Maximization

A.3 Model to Minimize Flood Risk by increasing maximum storage capacity

```
MODEL:
SETS:
  SET_R1: Ra;
  SET_S1: Sa;
  SET_ET: ET;
  SET_Q1: Qa;
  SET_T1: Time;
  SET_T2: Time2;
  SET_D: D;
ENDSETS
DATA:
  SET_S1 = Sa1..Sa13;
  SET_R1 = Ra1..Ra12;
  SET_Q1 = Qa1..Qa12;
  SET_ET = ET1..ET12;
  SET_D = D1..D12;
Time = 1 2 3 4 5 6 7 8 9 10 11 12;
Time2 = 1 2 3 4 5 6 7 8 9 10 11 12 13;
Qa = 2079 2354 1898 1456 998 702 535 349 225 459 696 1751;
ET = 2 2 2 1 1 0 0 1 2 3 5 4;
D = 208 208 208 208 74 74 16 16 16 16 74 208;
ENDDATA
SUBMODEL storage:
  MIN = K;
  @FOR(SET_T1(t) | t #LE# 12:
    Sa(t+1) = Sa(t) + Qa(t) - Ra(t) - ET(t));
  @FOR(SET_T1(t):
     Ra(t) >= D(t));
  @FOR(SET_T1(t):
     Ra(t) >= D1);
@FOR(SET_T1(t):
     Sa(t) >= Qa(t));
  @FOR(SET_T2(t):
    Sa(t) <= K);
  Sa(13) >= Sa(1);
ENDSUBMODEL
CALC:
  @SOLVE(storage);
ENDCALC
END
```

Listing 3: LINGO Code for Flood Risk Minimization