



**CLIMATE-RESILIENT DAMS AND
HYDROPOWER INFRASTRUCTURE
INTEGRATING
ENVIRONMENTAL SUSTAINABILITY
IN PLANNING AND DEVELOPMENT**

**ADAPTIVE HYDROPOWER INFRASTRUCTURE UNDER
CLIMATE UNCERTAINTY: INSIGHTS FROM INDIA**

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Background

- ❑ Climate change altering global hydrological cycles
- ❑ Increased floods, droughts, GLOFs, cloudbursts
- ❑ Traditional dam design based on stationarity assumptions
- ❑ These assumptions are no longer valid.
- ❑ Addressing these issues requires a systemic shift toward participatory, transparent, and risk-sensitive water governance frameworks that can respond dynamically to evolving hydrological realities
- ❑ Focus: actionable pathways for climate adaptation and water security in India and beyond



Importance of Dams in India



- ❑ Dams support irrigation, flood control, and hydropower
- ❑ Hydropower \approx 12% of India's installed capacity
- ❑ Energy security closely linked to dam reliability
- ❑ Aging infrastructure dominates the dam portfolio



Climate Change as a Risk Multiplier



- Intensified monsoon variability
- Himalayan glacier retreat
- Increased sediment inflow
- Compound and cascading hazards



Hydrological Non-Stationarity



- ❑ Historical flow records no longer reliable
- ❑ Floods exceed original design envelopes
- ❑ Longer droughts followed by intense rainfall
- ❑ Challenges both Himalayan and peninsular basins
- ❑ Dams designed under historical climate assumptions now operate under hydrological conditions that deviate sharply from their intended design envelopes



Key Operational Risks



- Overtopping during extreme floods
- Sedimentation reducing live storage
- Inadequate spillway capacity
- Turbine abrasion and efficiency loss
- Increasing maintenance and downtime



Sedimentation as a Climate Threat



- ❑ Accelerated erosion due to glacier retreat and deforestation
- ❑ High silt loads in Himalayan rivers
- ❑ Severe capacity loss in older reservoirs
- ❑ Impacts flood management and power generation



Indian Disaster Case Studies



- ❑ 2013 Kedarnath floods
- ❑ 2021 Chamoli avalanche-induced flood
- ❑ 2023 Teesta GLOF
- ❑ Revealed design, monitoring, and governance gaps



Global Case Studies



- ❑ Derna Dam failure (Libya, 2023)
- ❑ Arbaat Dam failure (Sudan, 2024)
- ❑ Hydropower disruption in Amazon & Alps
- ❑ Climate extremes + governance failures



Socio-Economic Impacts



- ❑ Loss of life and livelihoods
- ❑ Displacement of downstream communities
- ❑ Disruption of irrigation cycles
- ❑ Energy insecurity and social conflict



Governance and Institutional Issues



- ❑ Fragmented responsibilities across agencies
- ❑ Limited data sharing
- ❑ Weak enforcement of safety standards
- ❑ Inter-state and inter-sectoral conflicts

Need for Climate Resilient Framework

- **Escalating Challenges**
 - Hydrological non-stationarity, aging infrastructure, and socio-political fragility
 - Traditional deterministic design approaches are no longer adequate
- **Aging Infrastructure Challenges**
 - Over 80% of large dams older than 25 years
 - About 300 dams exceed 50 years
 - Outdated spillway capacity
 - Limited instrumentation and monitoring
- **In summary, the convergence of hydrological non-stationarity, infrastructure aging, and socio-political fragility presents a multidimensional challenge for India's dam sector**
 - Move beyond deterministic design
 - Integrate climate projections
 - Risk-based and adaptive approaches
 - Continuous reassessment of safety parameters



Inflow Design Flood (IDF) Evolution



- ❑ Traditional SPF and PMF methods
- ❑ Climate-informed IDF estimation
- ❑ Probabilistic and scenario-based analysis
- ❑ Inclusion of GLOFs and compound events



Role of Technology



- ❑ Remote sensing and GIS for catchment analysis
- ❑ Satellite rainfall and snowmelt data
- ❑ IoT-based real-time dam monitoring
- ❑ Early warning systems



AI and Machine Learning Applications



- ❑ Flood forecasting models
- ❑ Sediment load prediction
- ❑ Structural health monitoring
- ❑ Digital twins for dam simulation



Structural & Hydraulic Adaptations



- ❑ Labyrinth spillways
- ❑ Fuse plugs for controlled failure
- ❑ Dam heightening and freeboard increase
- ❑ Spillway capacity enhancement



Adaptive Reservoir Operations



- ❑ Dynamic rule curves
- ❑ Forecast-based pre-release strategies
- ❑ Flexible flood cushion management
- ❑ Improved drought resilience



Policy Initiatives in India



- ❑ Dam Safety Act (2021)
- ❑ National Dam Safety Authority (NDSA)
- ❑ Dam Rehabilitation and Improvement Project (DRIP)
- ❑ Growing focus on climate resilience

Key Conclusions

- ❑ Climate change invalidates static dam design
- ❑ Engineering solutions must align with governance reform
- ❑ Data-driven, adaptive, participatory frameworks are essential
- ❑ India can become a global model for climate-resilient dams



Thank You