Climate Change Induced Extreme Rainfall and Its Impacts on Large Reservoir Systems: A Non-Stationarity Perspective

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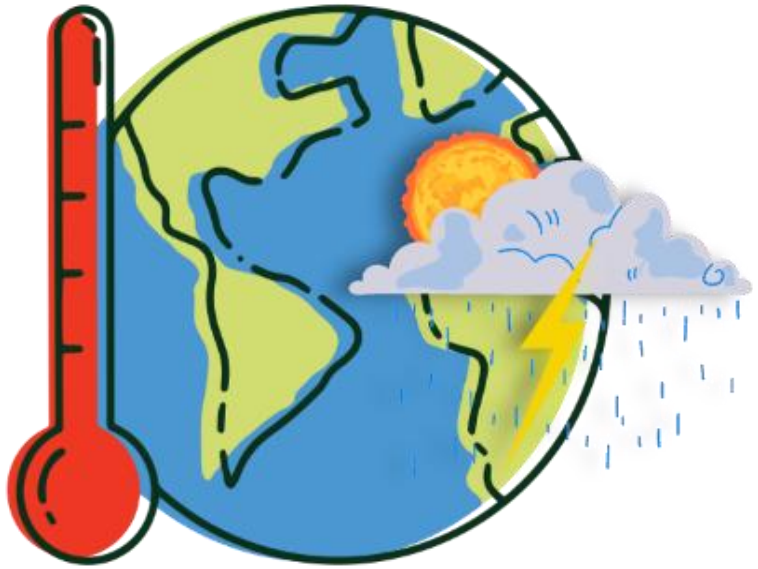
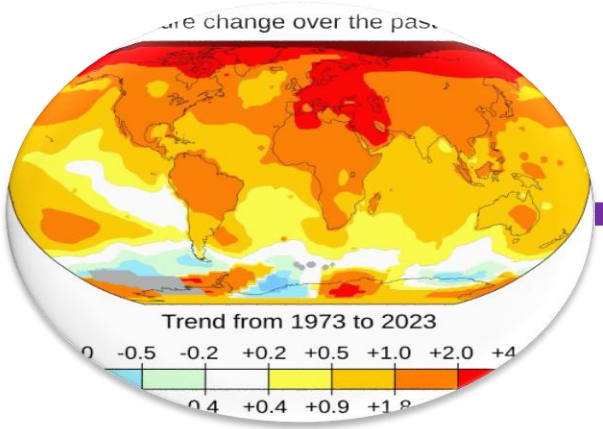
Graphical Abstract



Extreme Rainfall Assessments

Important Dams of India is defined as dams with height ≥ 100m or gross storage ≥1000MCM

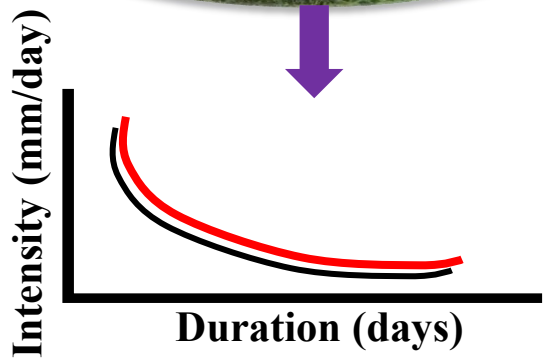
Motivation



A Warming Climate

More Extreme Rainfall Events

Rising Flood Risk for Dams



-Past (Stationarity climate)

-Future (Changing climate)

Research Questions ?

1. Are extreme rainfall events increasing in frequency and magnitude ?
2. How will future climate alter IDF curves and PMP estimates ?
3. Can stationary design assumptions still ensure reservoir safety ?

For example,

Tivare Dam

02nd July 2019

Annamayya Dam

19th November 2021

Are dams safe under successive extreme rainfall events in a changing climate ?

Focus

To assess the impacts of climate change on extreme rainfall characteristics and their implications for large reservoirs in the Godavari River Basin (GRB), India.

Table 1. NEX-GDDP-CMIP6 GCMs

S. Letter	GCM Name
A	ACCESS-CM2
B	ACCESS-ESM15
C	BCC-CSM2-MR
D	CanESM5
E	CMCC-CM2-SR5
F	CMCC-ESM2
G	EC-Earth3
H	EC-Earth3-Veg-LR
I	GFDL-CM4-GR1
J	GFDL-CM4-GR2
K	GFDL-ESM4
L	IITM-ESM
M	INM-CM4-8
N	INM-CM5-0
O	IPSL-CM6A-LR
P	KACE-1-0-G
Q	MIROC6
R	MPI-ESM1-2-HR
S	MPI-ESM1-2-LR
T	MRI-ESM2-0
U	NESM3
V	NorESM2-LM
W	NorESM2-MM
X	TaiESM1

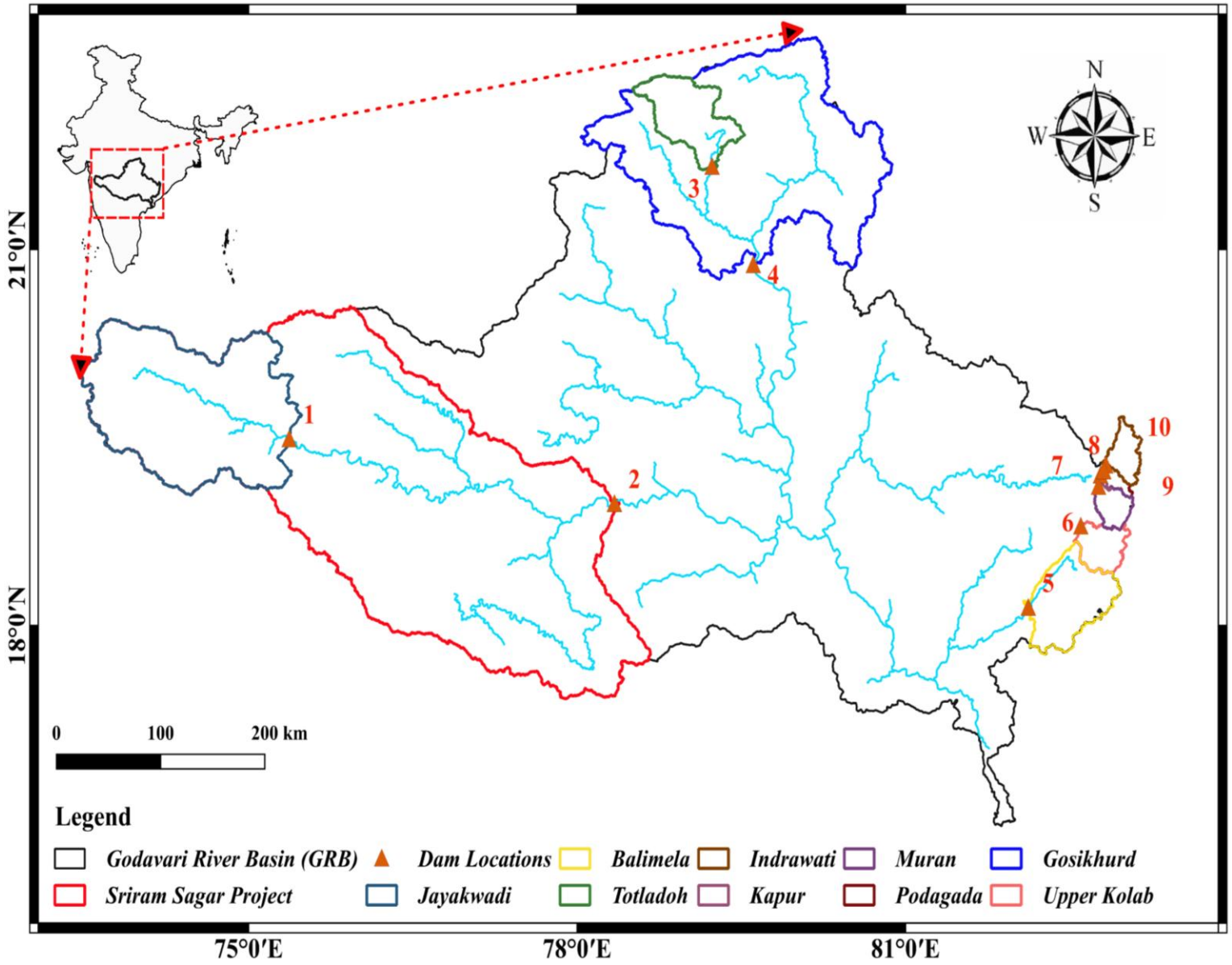


Figure 1. Geographical location of 10 important dams considered in the study area.

Table 2. Salient features of selected dams (Source: https://dharma.ndsa.gov.in/#/national-register-of-specified-dams-(nrsd)-2025).

S. No	Dam Name	Built Year	Type	River	Height (m)	Length (m)	Area of Catchment (km^2)	Purpose	Gross Storage (MCM)	Spillway Capacity (m^3/s)
1	Jayakwadi	1976	Earthen	Godavari	41	9998	22200	Multipurpose	2909.04	18153
2	Sriram Sagar Project	1983	Composite	Godavari	43	14576	90100	Multipurpose	2279.50	45307
3	Totladoh	1989	Earthen	Pench	75	3061	4310	Hydro-Power	1166.93	12072
4	Gosikhurd	2008	Earthen	Maru	44	11356	35100	Irrigation	1146.08	67300
5	Balimela	1972	Earthen	Sileru/Machukund	92	2083	4920	Multipurpose	3610	14300
6	Upper Kolab	1988	Composite	Kolab/ Sabari	54	646	1640	Multipurpose	1235.00	10020
7	Muran	1996	Composite	Muran	65	591	1020	Multipurpose	2300	8588
8	Podagada	1996	Earthen	Poragar	77	462	370	Irrigation	2300	_
9	Upper Indrawathi	1996	Masonry Gravity	Poragar	45	539	1190	Multipurpose	2300	11985
10	Kapur	1996	Earthen	Kapur N	64	537	56	Multipurpose	2300	_

Framework

Data Acquisition

Observed Data (IMD)

Downscaled Climate Data (NEX-GDDP-CMIP6)

0.25^0 x 0.25^0

Ranking Framework

Level-1: Evaluation of GCMs for the Indian Mainland (IM)

Level-2: Evaluation of GCMs at the Basin Level using statistical parameters

Level-3: Multi-Criteria Decision-Making (MCDM) Analysis for IRBs

Level-4: Group Decision-Making (GDM) for Final Ranking of GCMs at Basin level

Selection of T_5 Best Performing Models for GRB

BCC-CSM2-MR | MPI-ESM2-HR | MPI-ESM2-LR | NESM3 | CMCC-ESM2

Analysis

Historical Period (1951-2014)

Non-Stationarity Assessment Methods

Epoch-wise | Trend | Change Point Detection

Significant Increase

Future Period (2015-2100)

SSP1-2.6 | SSP2-4.5 | SSP5-8.5

IDF Analysis

PMP Analysis

Practical Recommendations

Results and Discussions

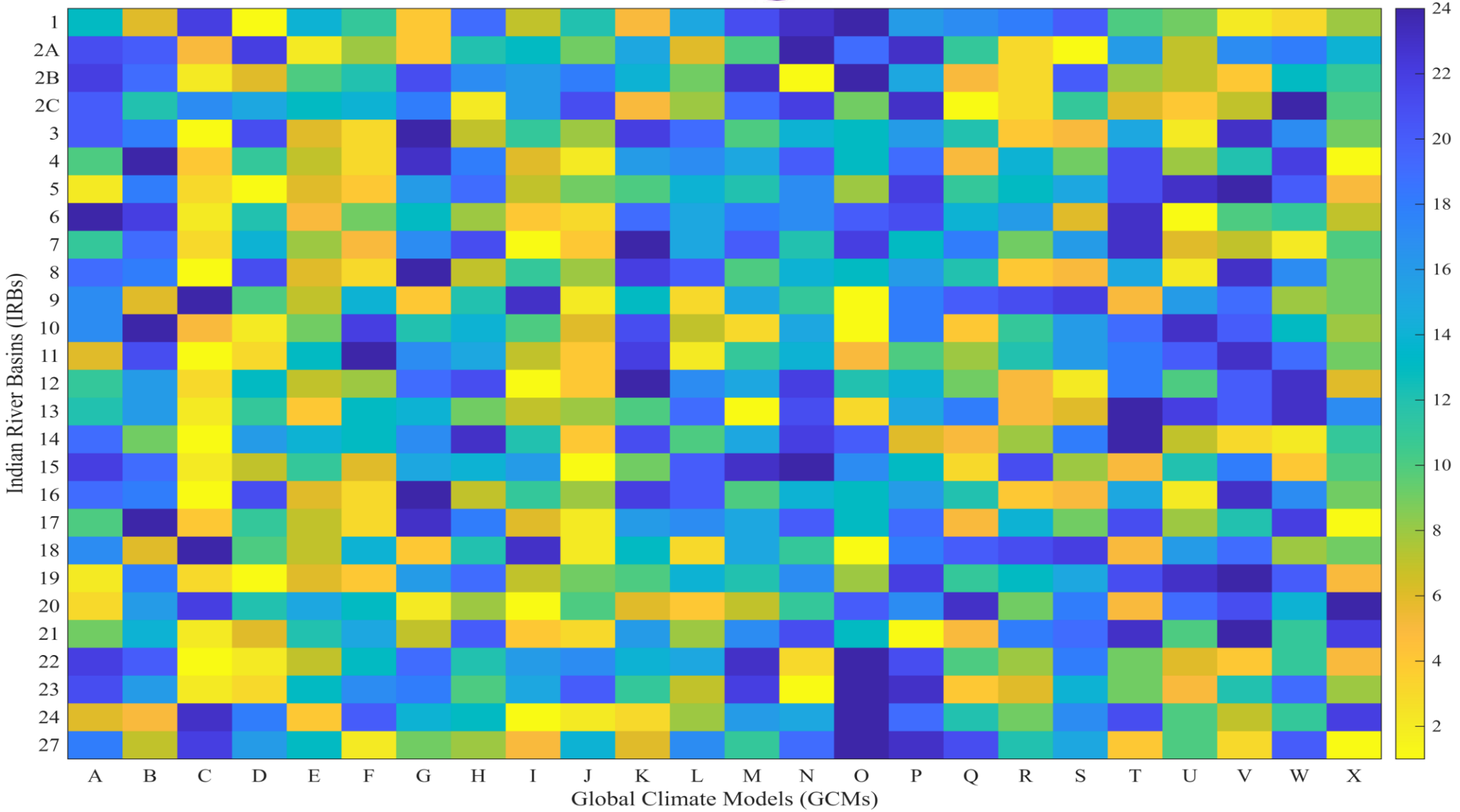


Figure 3. Final rankings of each GCM across IRBs using GDM approach based on all statistical metrics (Roulo et al., 2026)

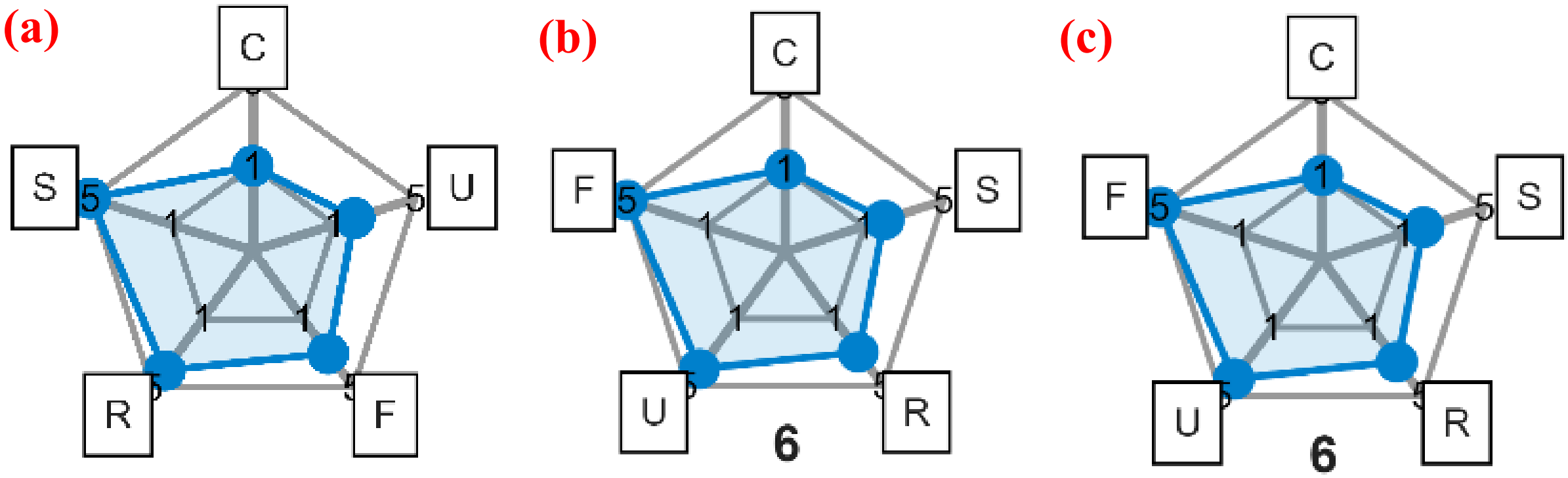


Figure 4. T_5 ranking GCMs for GRB using GDM approach: (a) all statistical metrics together, (b) error-based metrics, and (c) correlation- and efficiency-based metrics
(Roulo et al., 2026)

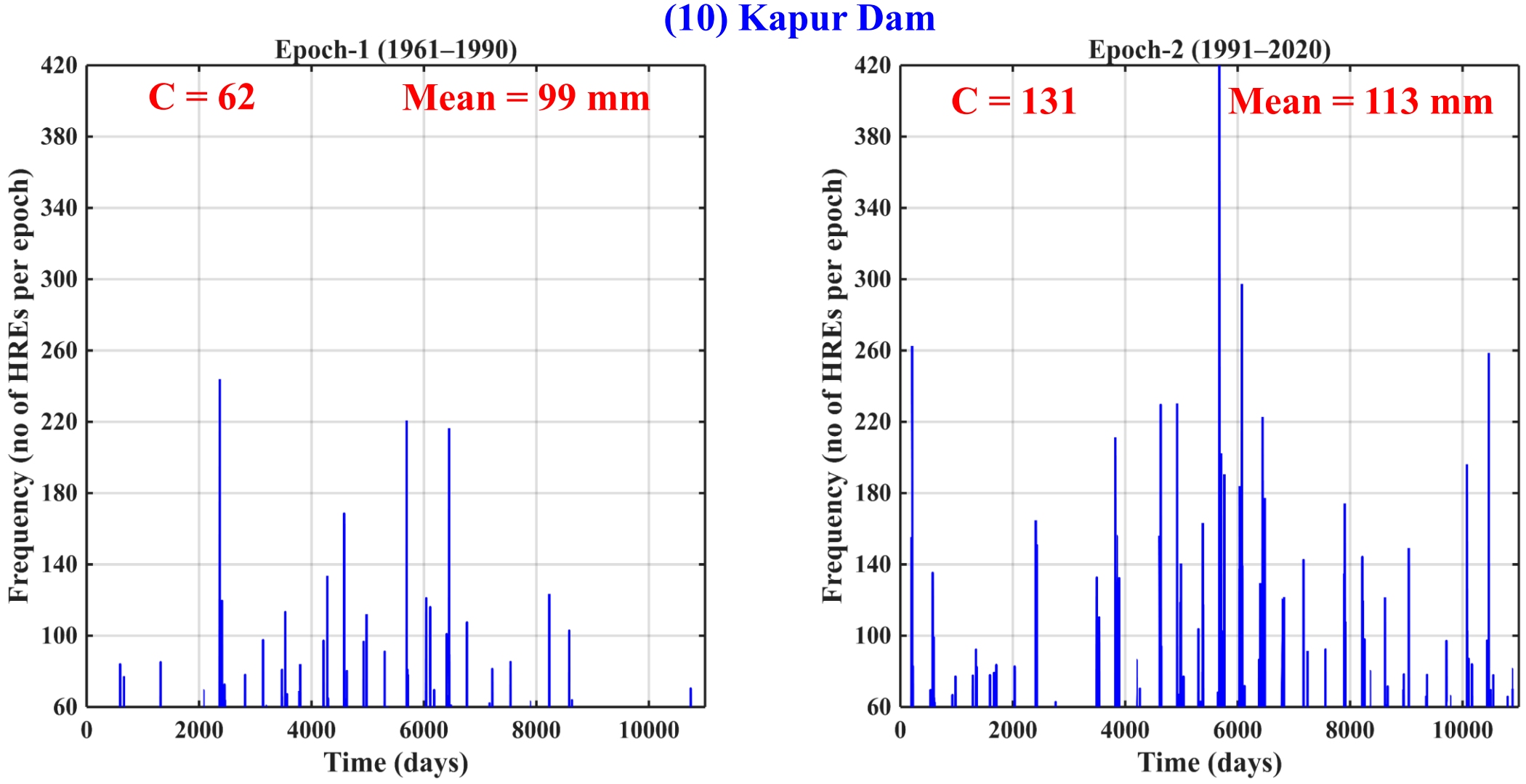
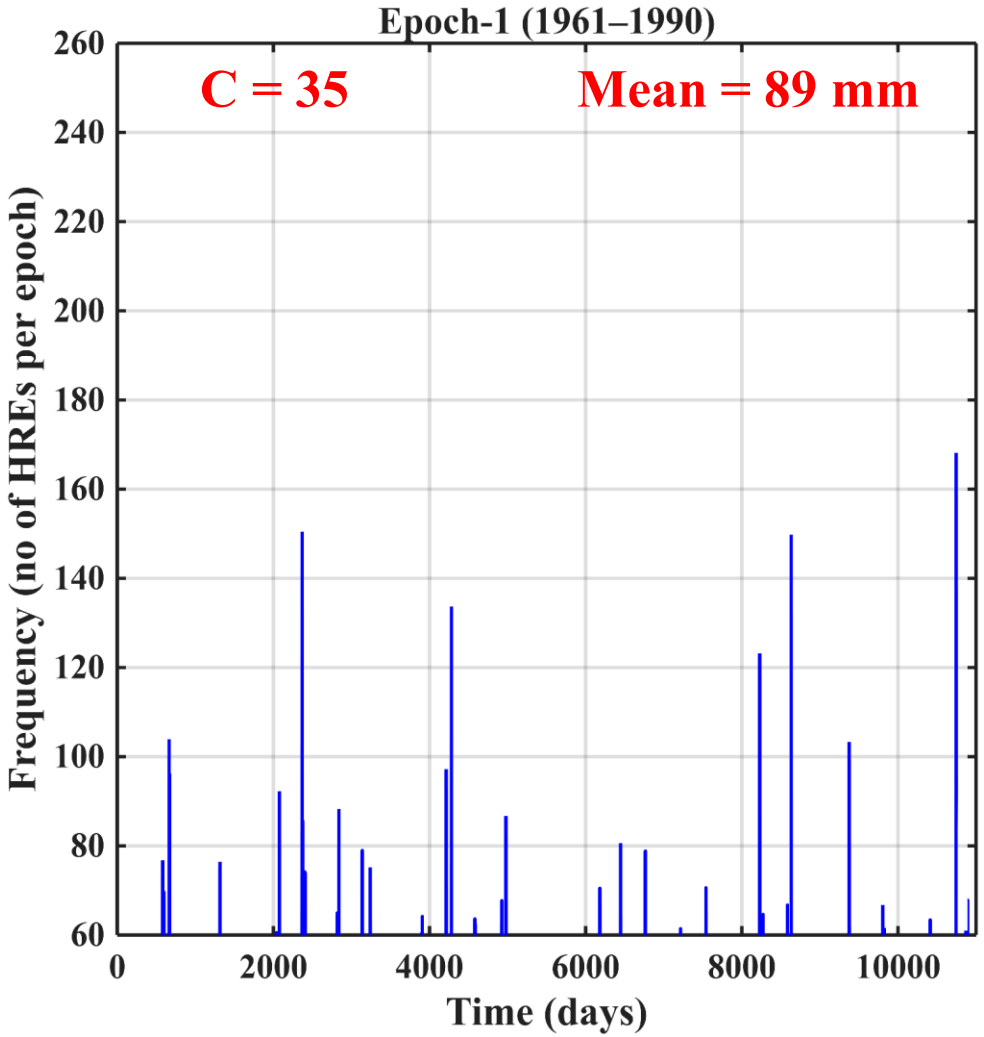
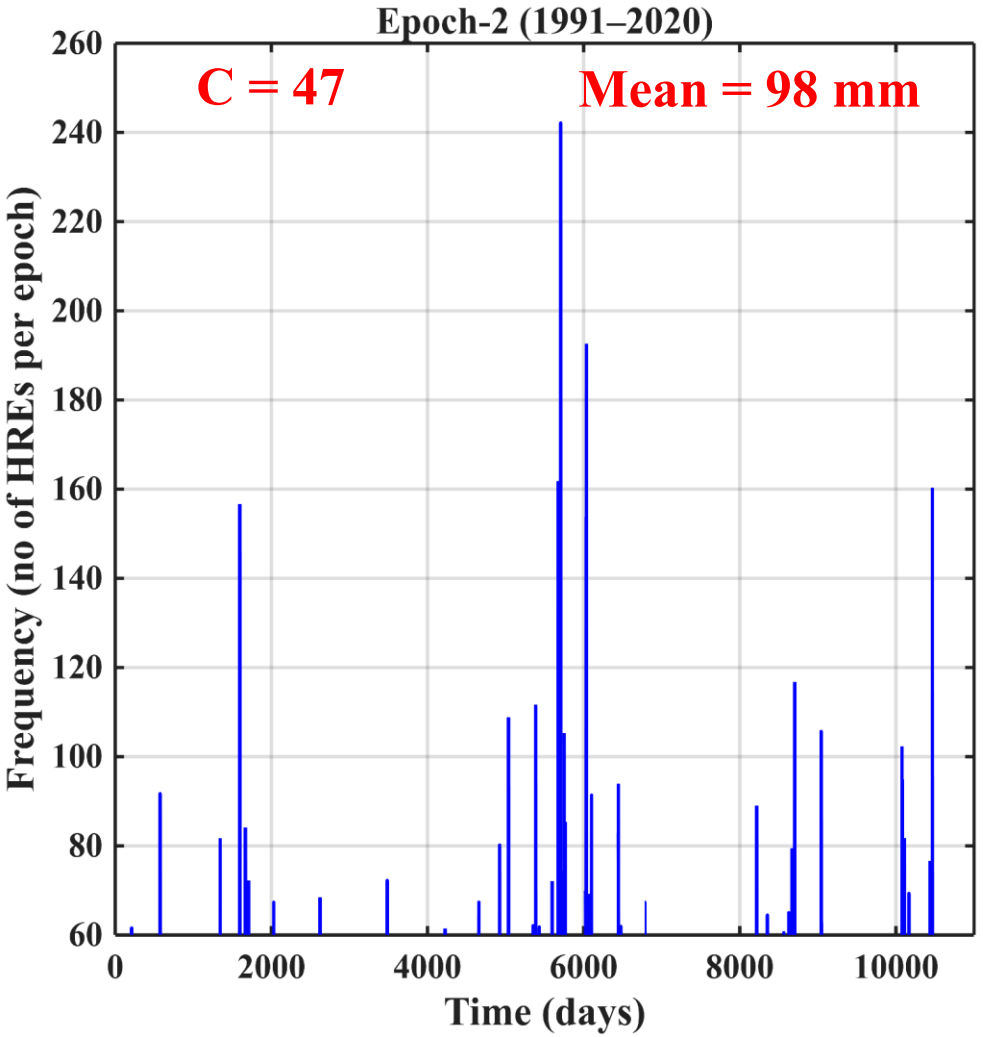


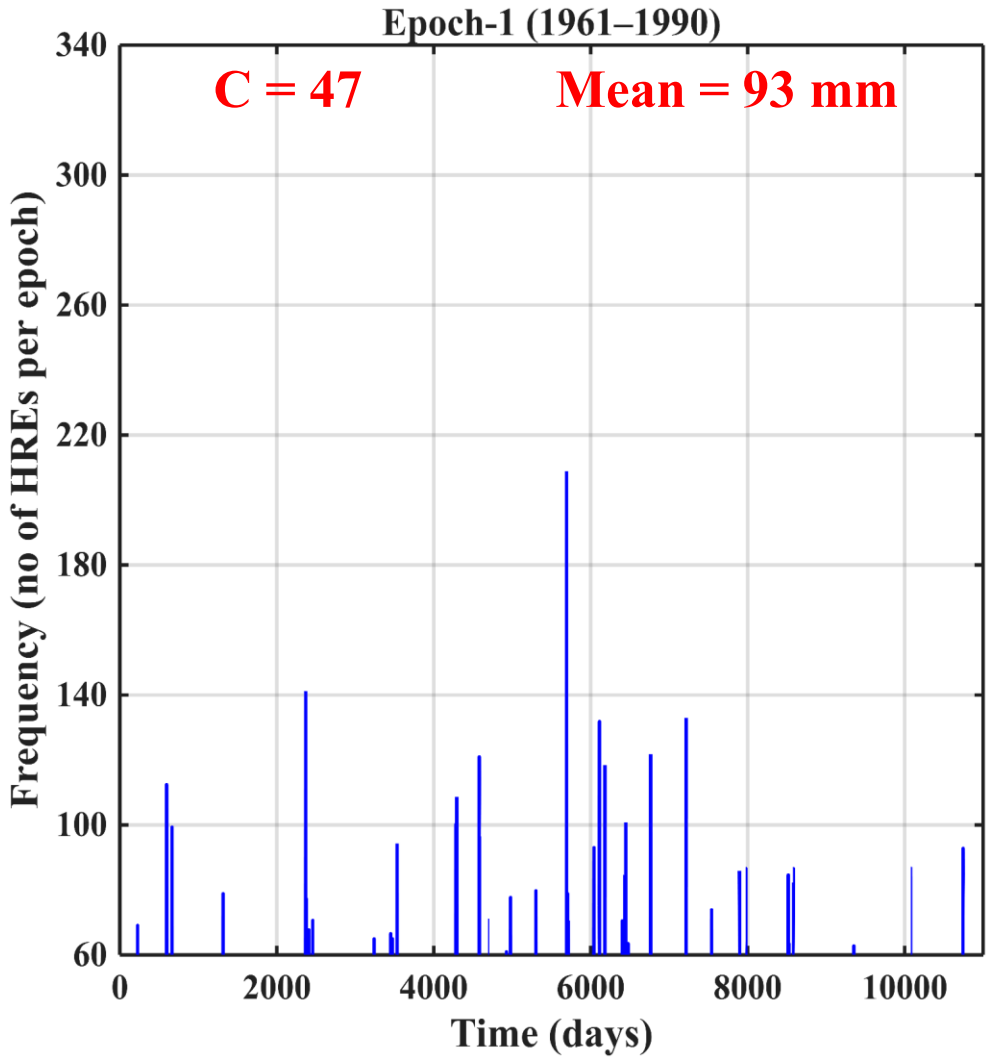
Figure 6. Frequency of heavy rainfall events (HREs) per epoch for Kapur dam, Muran dam, Upper Indrawathi dam, Upper Kolab dam. Each epoch represents a 30-year rainfall period: Epoch-1 (1961–1990), and Epoch-2 (1991–2020).

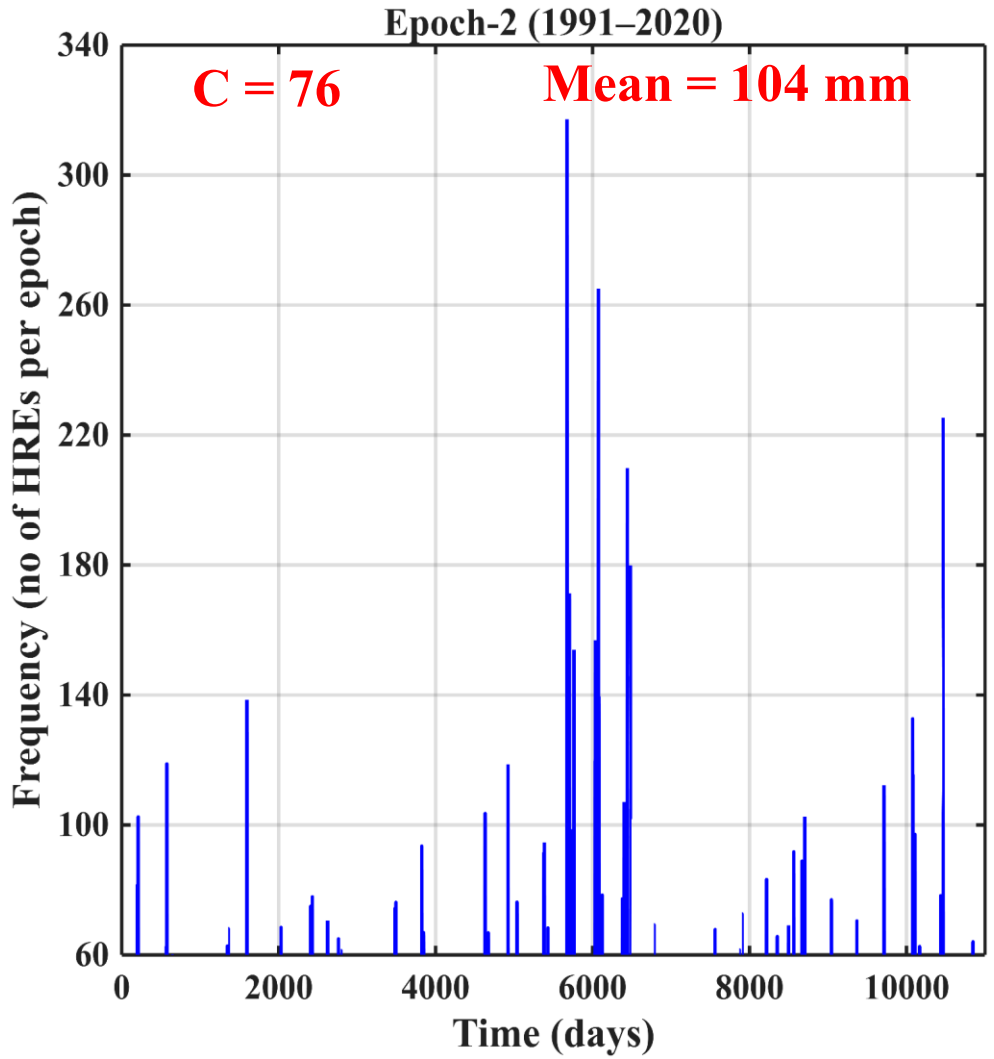
(7) Muran Dam


Epoch-1 (1961–1990)
C = 35
Mean = 89 mm
Frequency (no of HREs per epoch)
Time (days)
260
240
220
200
180
160
140
120
100
80
60
0
2000
4000
6000
8000
10000

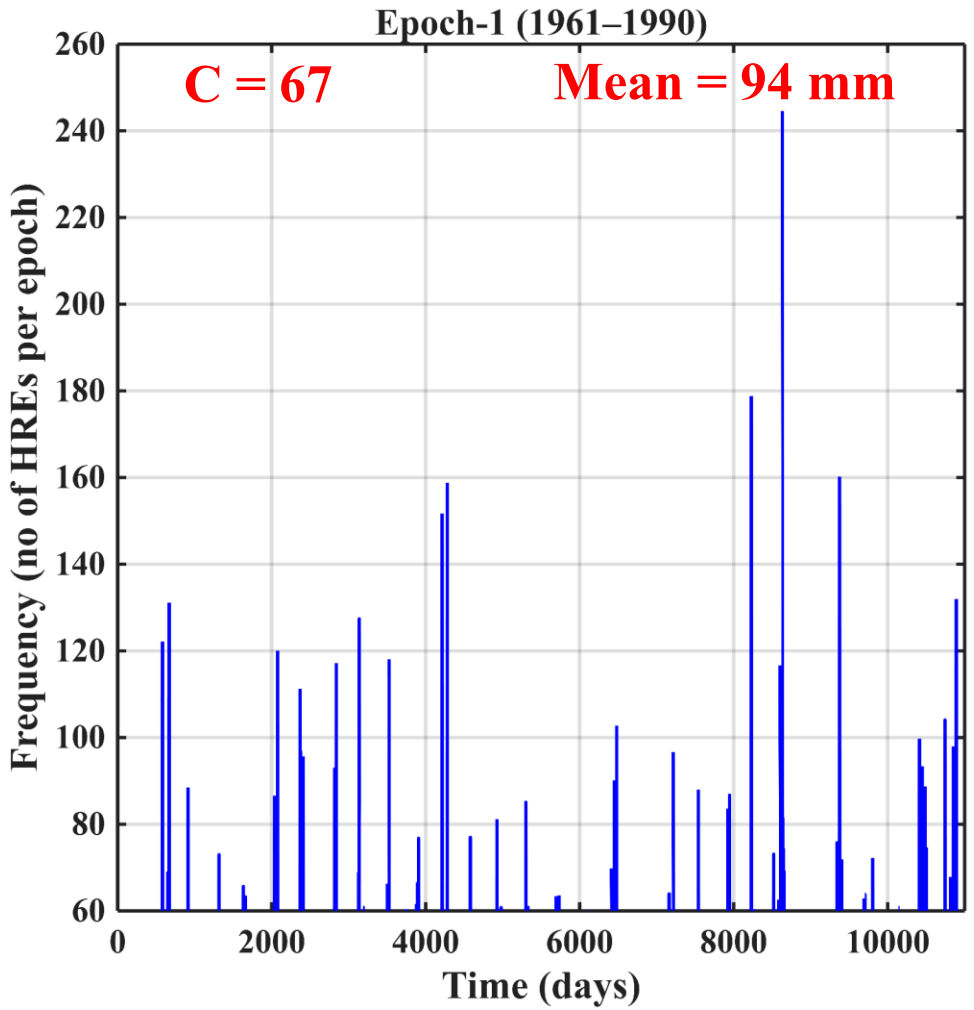

Epoch-2 (1991–2020)
C = 47
Mean = 98 mm
Frequency (no of HREs per epoch)
Time (days)
260
240
220
200
180
160
140
120
100
80
60
0
2000
4000
6000
8000
10000

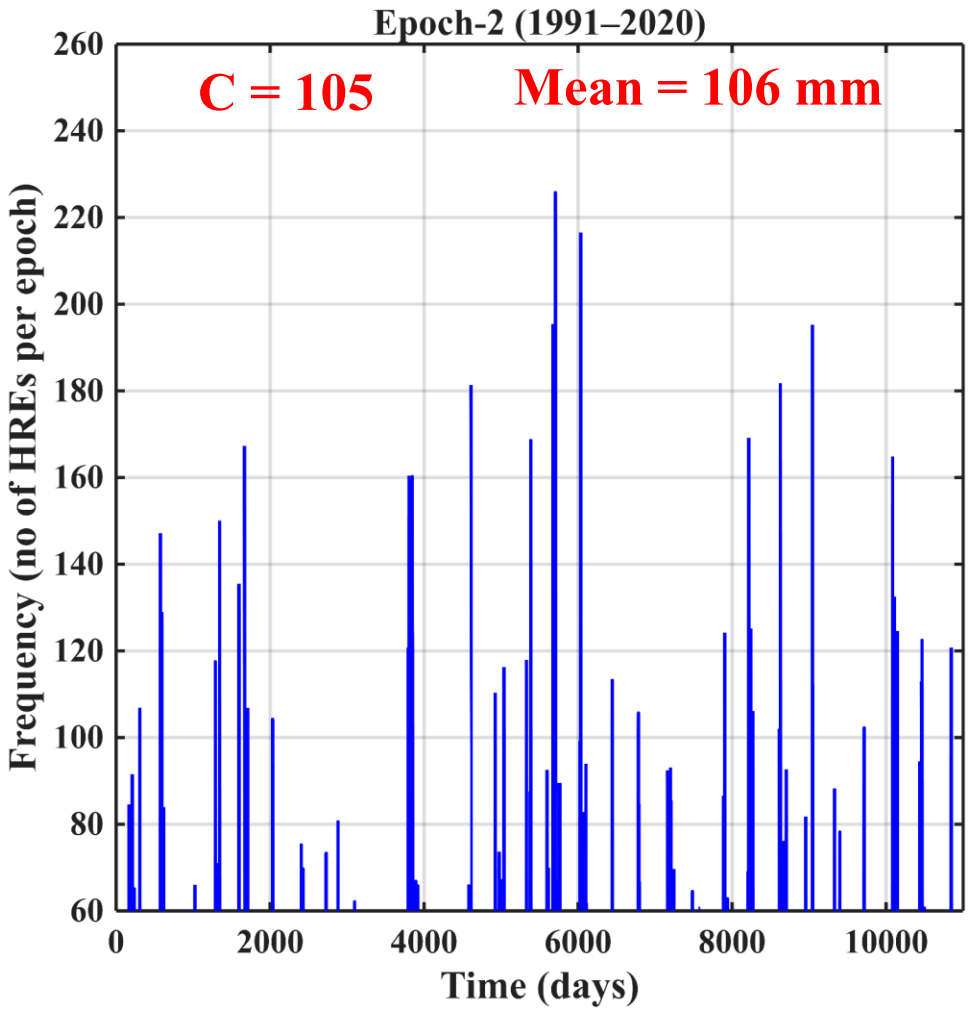
(9) Upper Indrawathi Dam

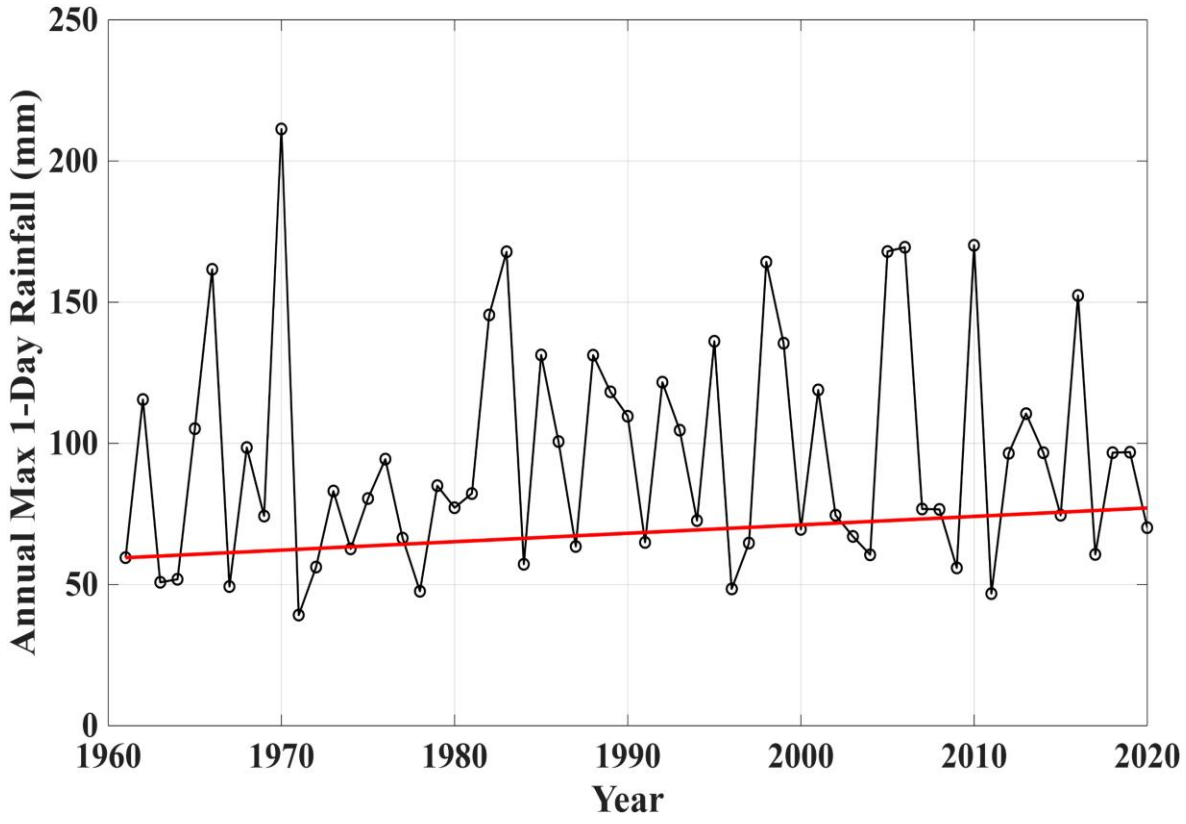




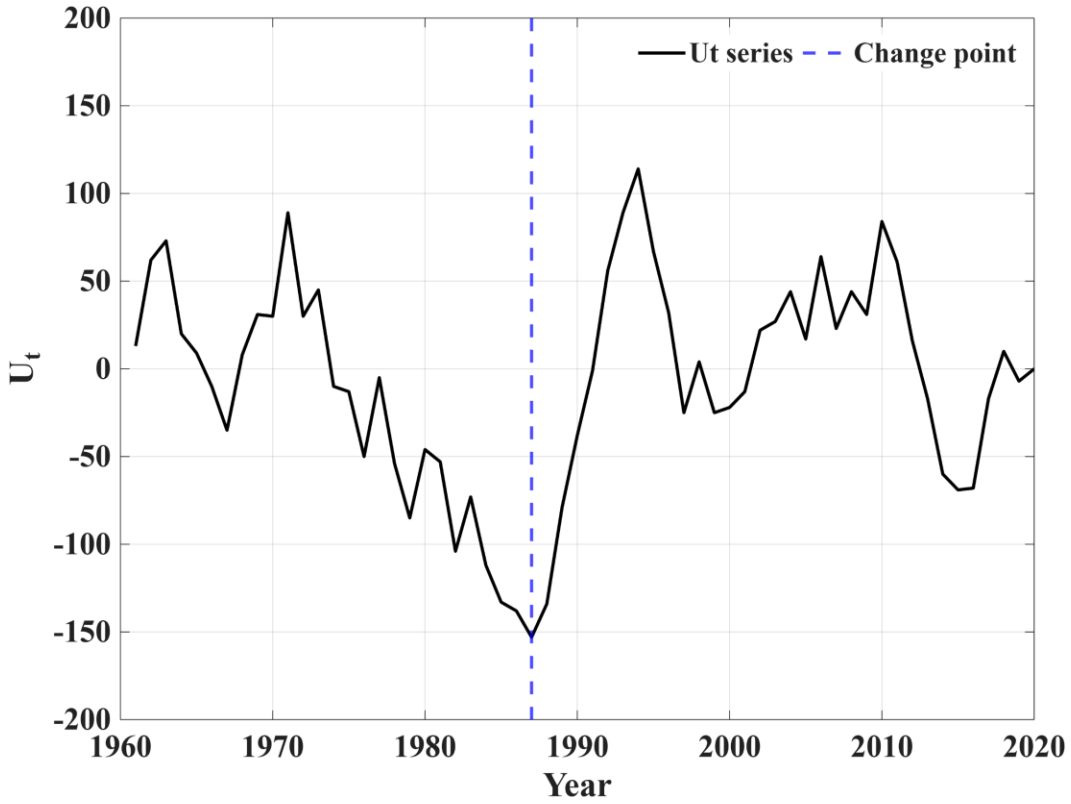
(6) Upper Kolab Dam







(a)



(b)

Figure 5. Statistical Results of (a) Mann-Kendall and Sen's Slope Estimator; (b) Pettitt's Test for Sriram Sagar Project

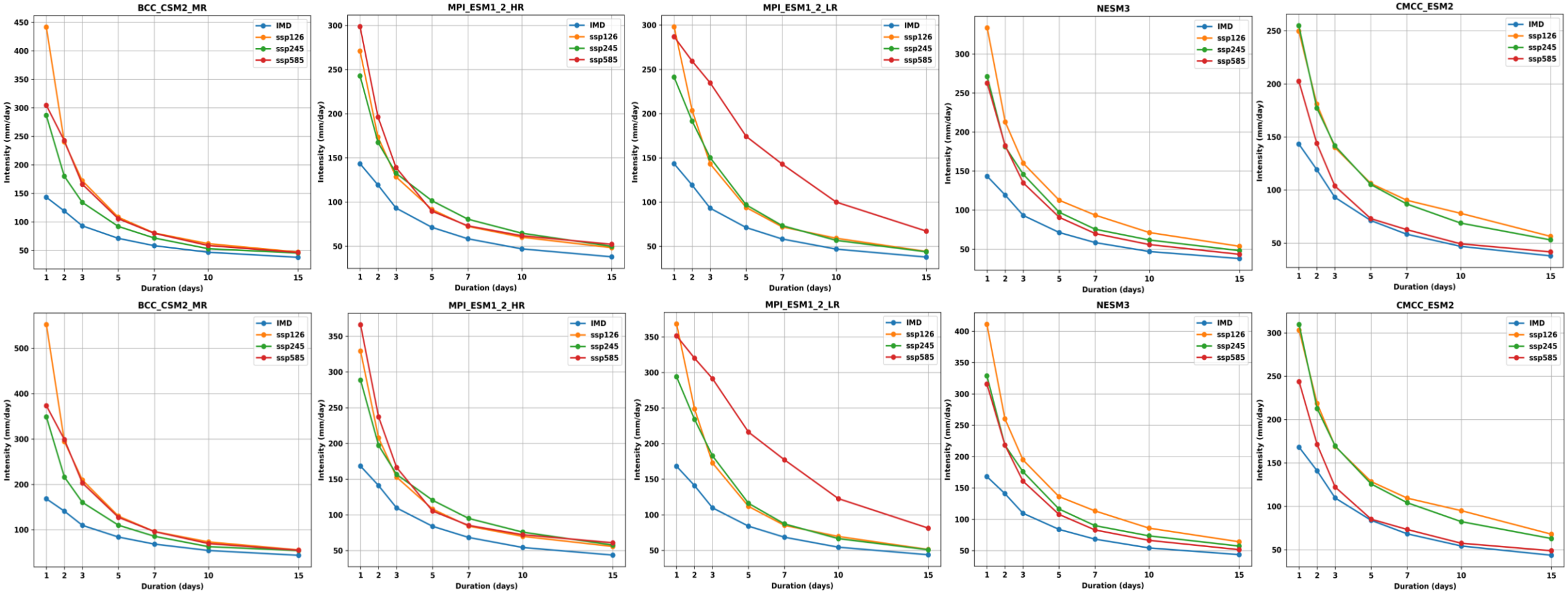
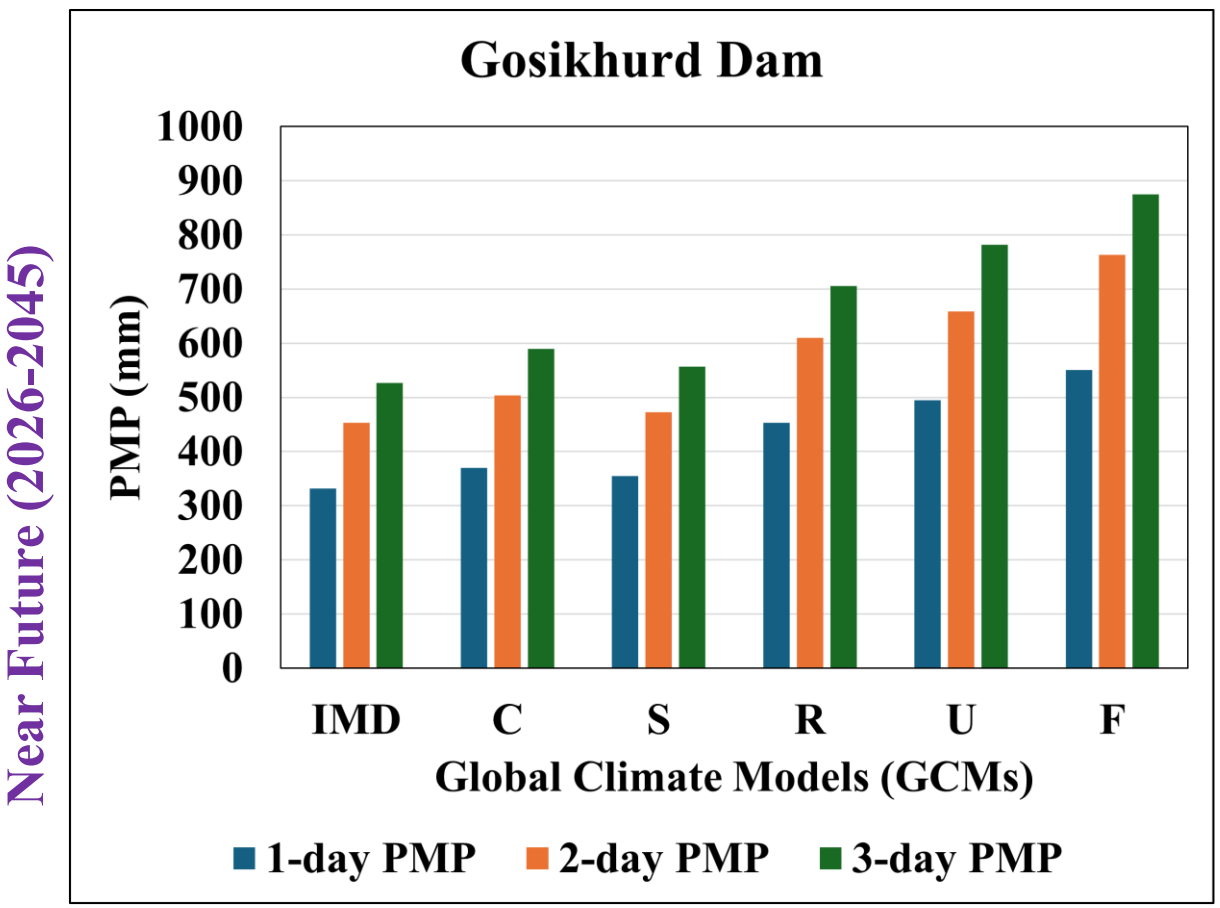


Figure 7. Comparison of intensity–duration–frequency (IDF) curves from future scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) with IMD (historical) data for Gosikhurd Dam.



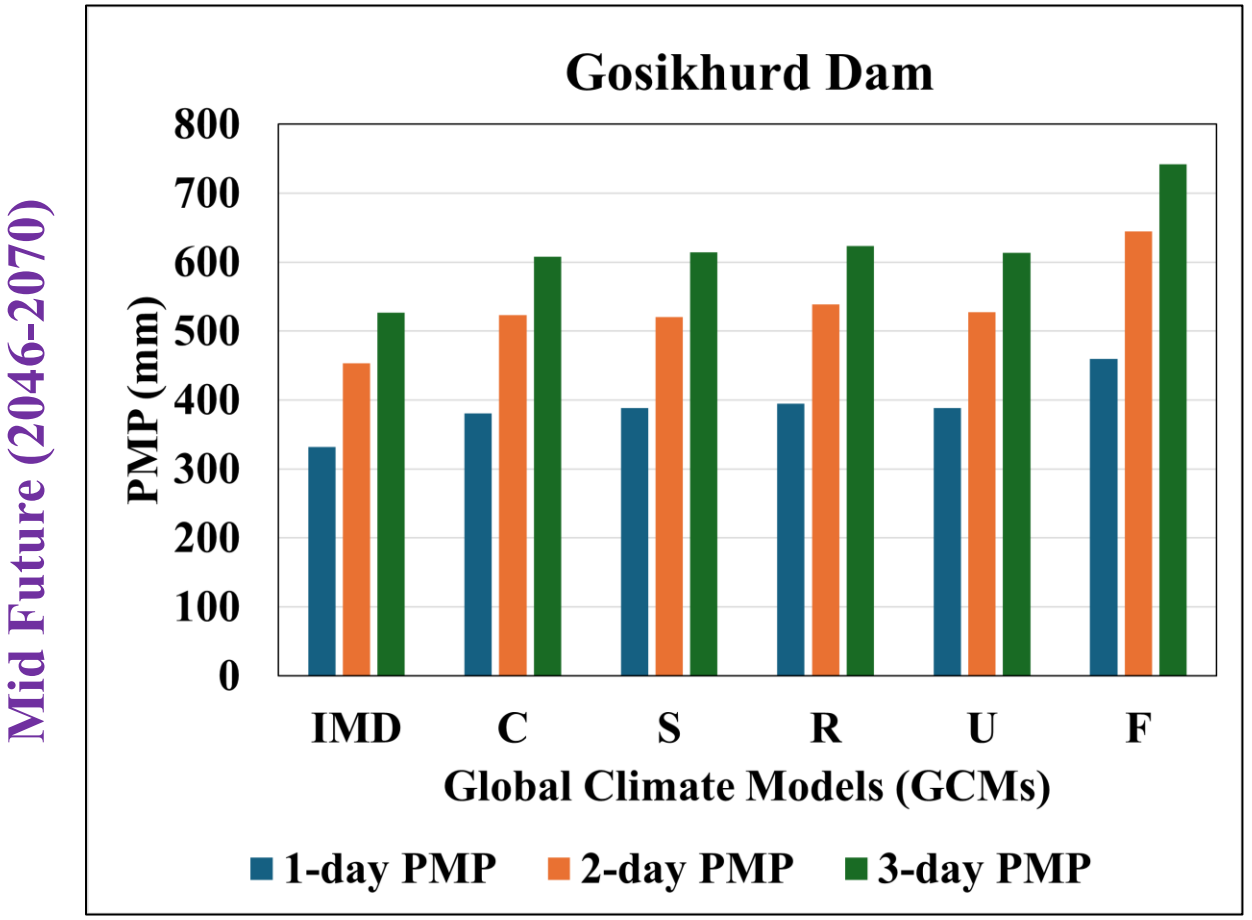


Figure 8. Projected PMP values (1-day, 2-day, 3-day) across T5 models and IMD for Gosikhurd dam.

Table 3. Projected 2-day PMP for each dam using top-three models for various future periods.

Dam Name	IMD	BCC-CSM2-MR			MPI-ESM1-2-HR			MPI-ESM1-2-LR		
		Near Future	Mid Future	Far Future	Near Future	Mid Future	Far Future	Near Future	Mid Future	Far Future
Balimela	890	1094	1124	1234	748	814	994	847	1134	1618
Gosikhurd	453	523	504	588	539	610	823	520	472	646
Upper Indrawathi	759	1139	1537	1533	732	1087	931	1072	1231	1284
Jayakwadi	356	415	702	439	1089	525	718	2398	764	1283
Kapur	913	815	1169	1177	926	1344	1003	1457	1665	1683
Muran	551	565	665	701	545	776	616	710	804	826
Podagada	926	832	1193	1196	941	1366	1016	1477	1688	1706
Sriram Sagar Project	349	449	493	512	616	462	504	498	1276	1156
Totladoh	465	474	558	657	457	568	1618	753	690	1162
Upper Kolab	615	842	913	1010	676	917	829	811	970	1258

Near Future (2026-2045)

Mid Future (2046-2070)

Far Future (2071-2100)

Takeaways

The following vital conclusions are made from this study.

1. **Extreme rainfall events are increasing across dams in the GRB, indicating intensification of hydrological extremes.**
2. **IDF curves exhibit a consistent upward shift under future scenarios, implying higher rainfall intensities for the same return periods.**
3. **PMP shows a significant increase, reflecting amplified extreme storm potential.**
4. **Historical stationary design approaches may underestimate future flood risks, highlighting the need for non-stationary, climate-informed design practices.**

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References

Roulo, D., S.Pichuka, and R. P.Menon. 2026. "From Global to Basin-Scale: Identifying Best-Performing CMIP6 Models Across Indian River Basins Through Downscaled Precipitation Products." International Journal of Climatologye70367. https://doi.org/10.1002/joc.70367.