



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

**National-Scale River Flow Prediction for
Climate-Resilient Dams and Hydropower
Planning in India**

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Founder Director INRM Consultants

(A R&D based company set up under TBIU plan of IIT Delhi)



Background

- India's dams and hydropower systems face increasing climate variability, floods and droughts.
- Reliable river flow forecasting is essential for climate-resilient operations.



Why Flood and Flow Forecasting?



- Floods cause major loss of life and assets.
- Dry spells affect hydropower and water supply.
- Advance forecasts improve reservoir operations and safety.

Steps for Flow Forecasting

- IMD provides high-resolution rainfall forecasts.

WRF (Weather Research and Forecasting) Model

- 9 km resolution

GFS (Global Forecast System) Model

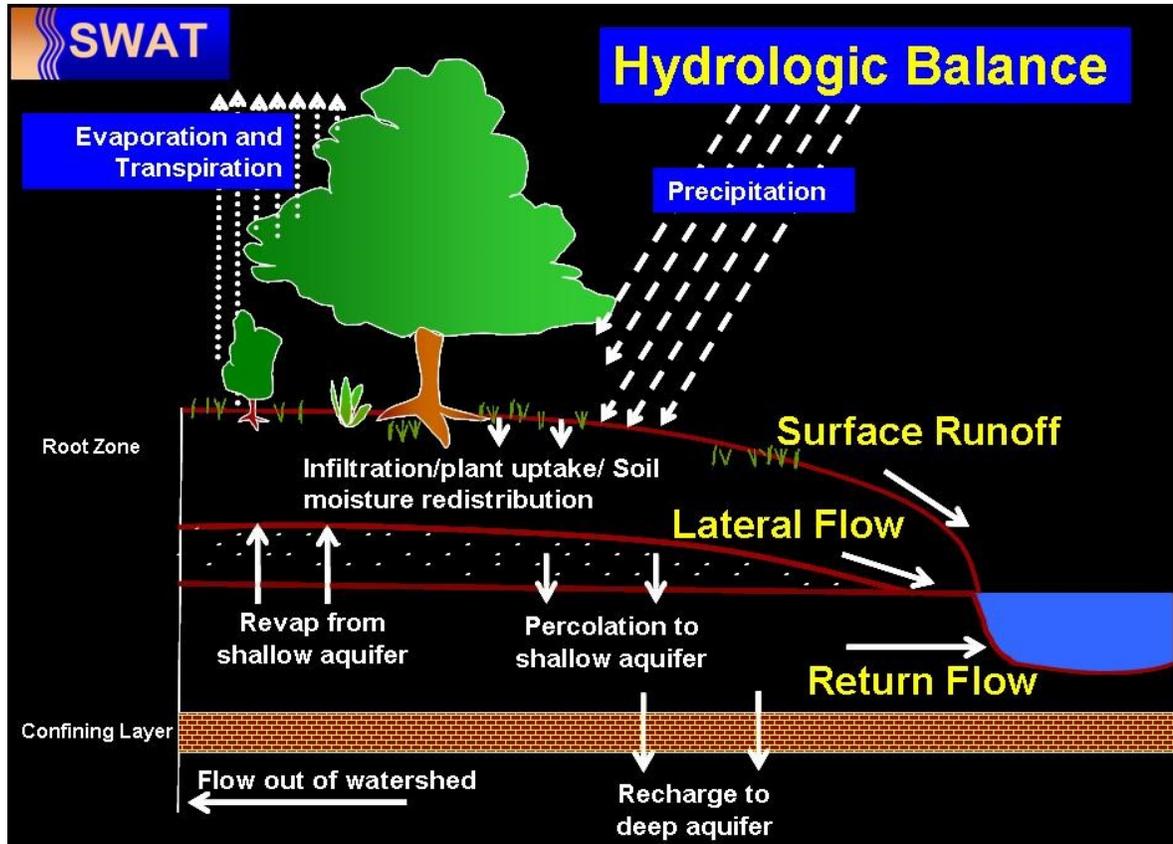
- 12.5 km resolution

NOAA GFS Model

- 37.5 km resolution

- These can be translated into river flows using hydrological models.

Hydrological model - SWAT (Soil and Water Assessment Tool)



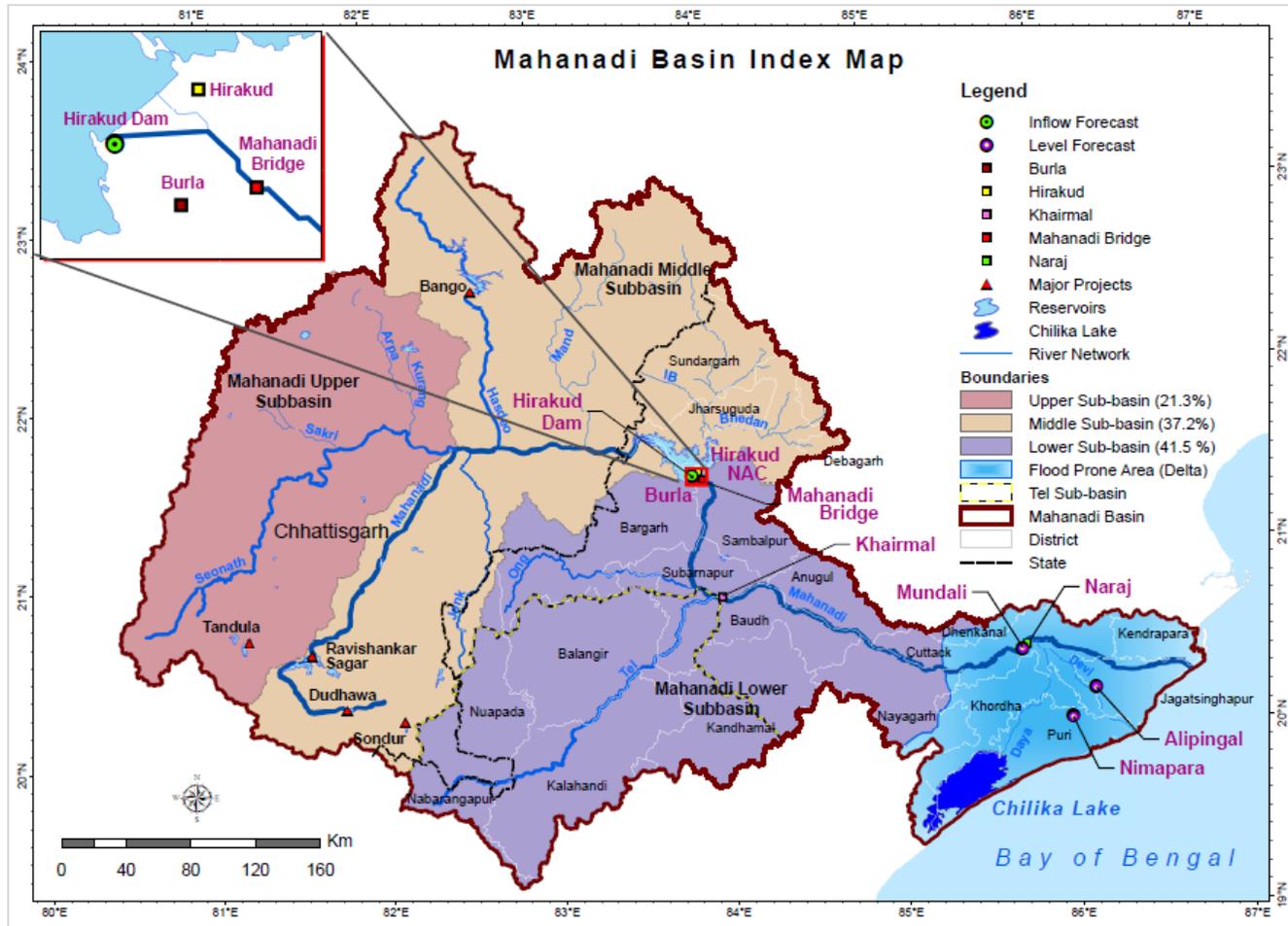
- Features
 - Physically based
 - Distributed model
 - Continuous time model (long term yield model)
 - Uses readily available data
 - Used for long term impact studies



Data used

- DEM
 - SRTM – 30m resolution
- Landuse (NRSA 2007-08)
- Soil – NBSSLUP/FAO
- Weather: IMD gridded rainfall, temperature
 - Observed rainfall
- Reservoir characteristics and operation rules
- Observed Stream Gauge and Discharge data of CWC

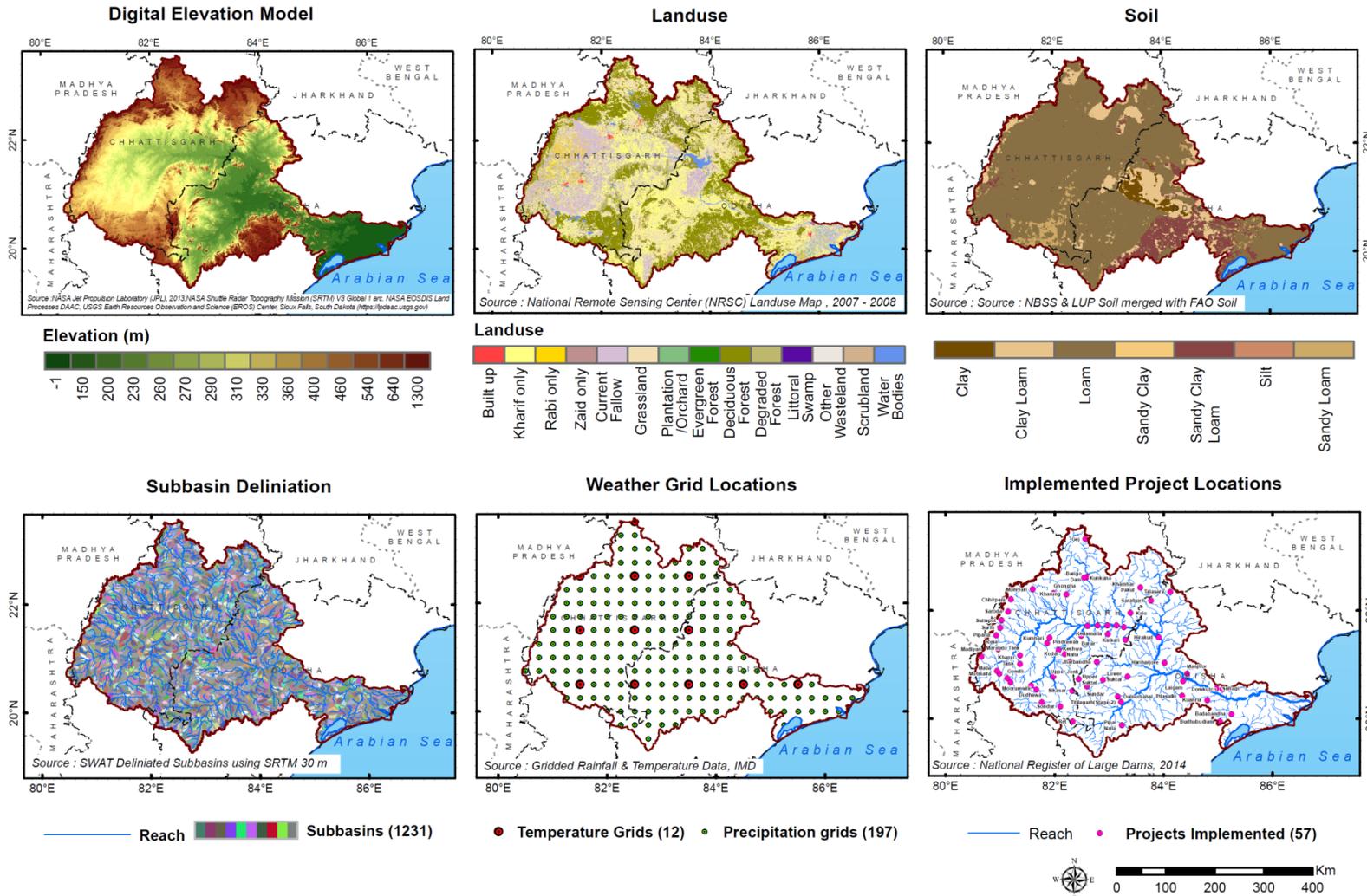
Mahanadi River Basin – Example



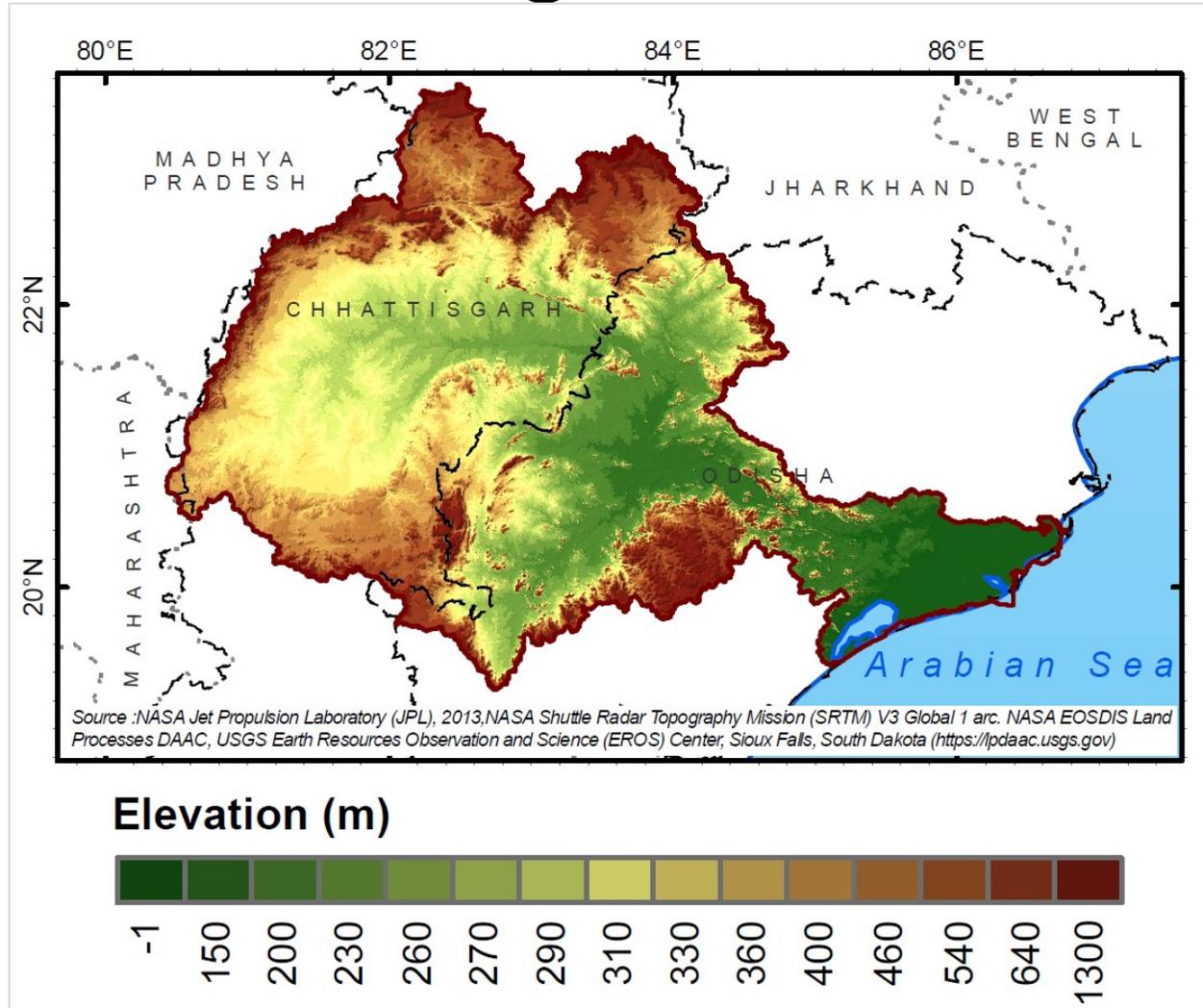
- Chhattisgarh (53%) and Odisha (46.3%)
- Chhattisgarh (357 km, 75,136 sq. Km.) and Odisha (494 km, 65,580 sq. Km.) [1,41,589 sq. km.]
- Seonath, Hasdeo, Mand and Ib that joins from left; Ong, Tel and Jonk joins from right
- Average annual rainfall in the basin at 1,438 mm
- 32 ARGs under Hydrology Project II
- CWC 39 gauge-discharge sites
- 4 flood forecasting stations
- 34 sites established by the State Governments
- 6 major projects: Hiramud Dam in Odisha, Ravishankar Sagar, Dudhawa Reservoir, Sondur Reservoir, Hasdeo- Bango and Tandula, all in Chhattisgarh

Input data used for SWAT modelling setup for Mahanadi River basin

Basic Spatial Data for SWAT Hydrological Modelling

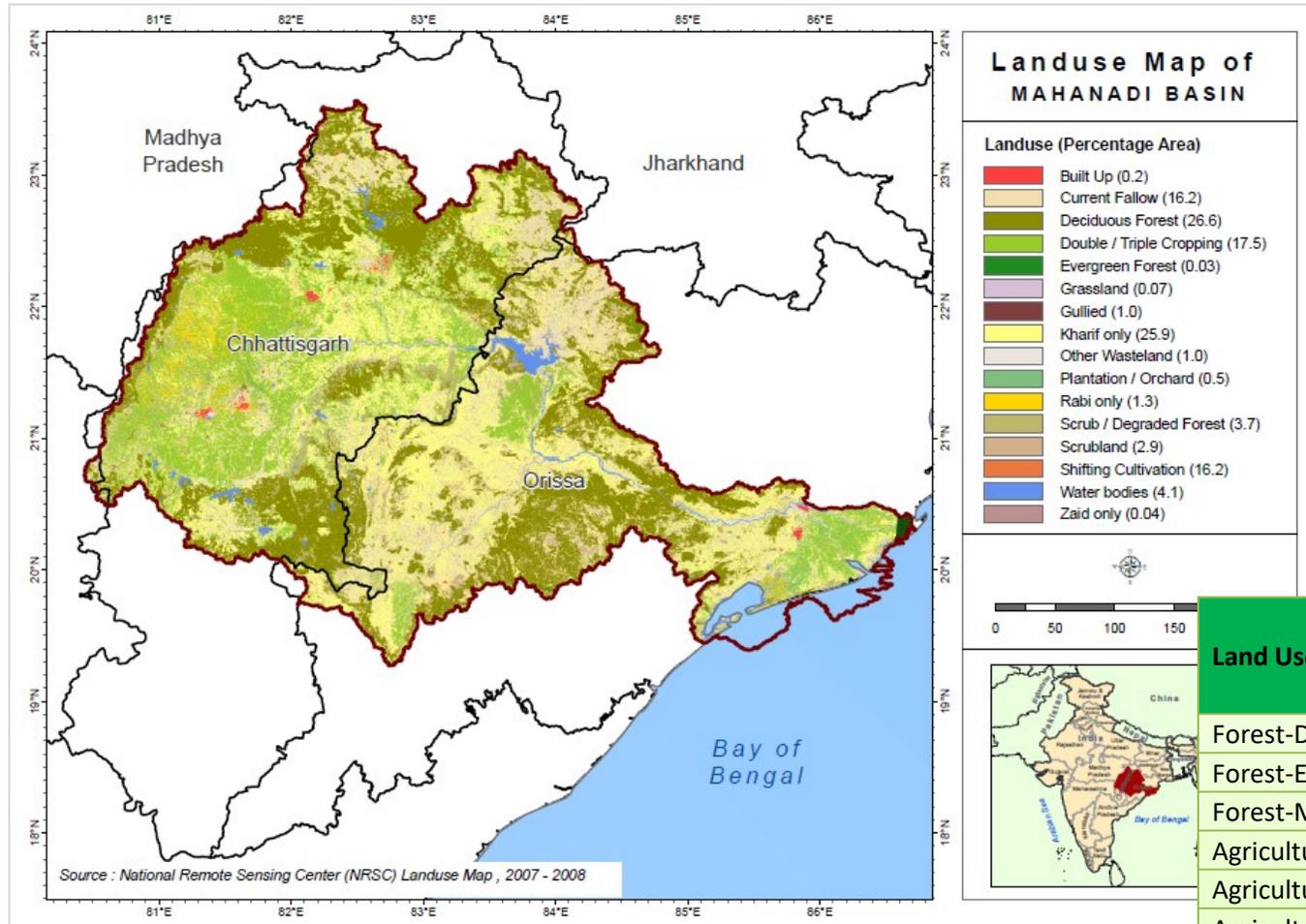


Basic Data layers for modelling- Digital elevation model



Parameter	Elevation (m)
Minimum Elevation	< 0
Maximum Elevation	1326
Mean Elevation	324

Land use Layer

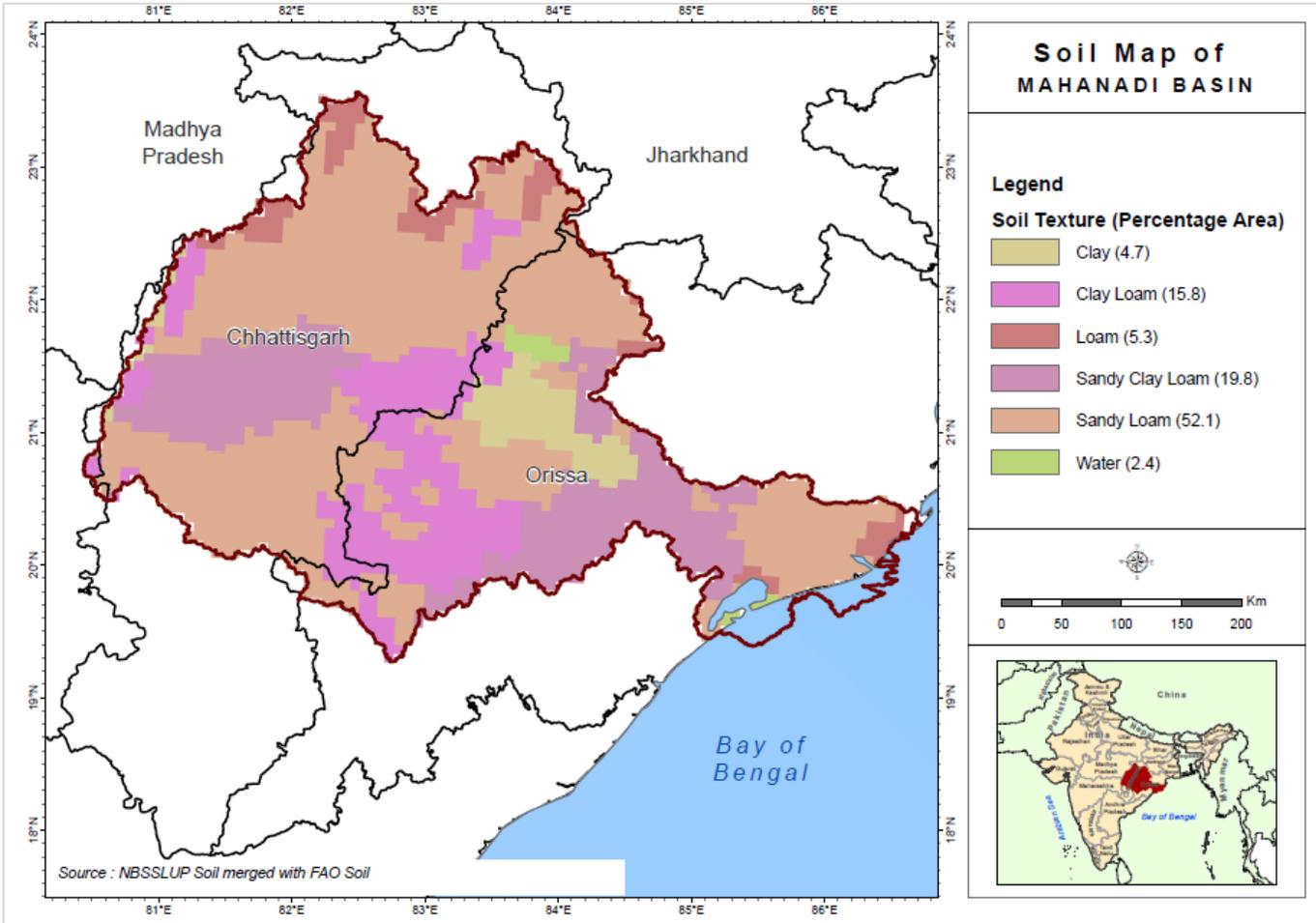


Predominantly Agriculture (62%) and Forest (30%)

Source : NRSC Landuse / Landcover Map (2007 - 2008)

Land Use	Area (ha)	% of Watershed Area
Forest-Deciduous	3,949,594	26.6
Forest-Evergreen	5,107	0.0
Forest-Mixed	548,443	3.7
Agriculture - Kharif	3,839,273	25.9
Agriculture - Rabi	339,064	2.3
Agriculture - Double/Triple Crops	2,595,755	17.5
Plantation/orchard	76,435	0.5
Current Fallow	2,409,669	16.2
Pasture/Rangeland	440,336	3.0
Water bodies	60,5142	4.1
Urban	25,945	0.2
Total	14,834,763	100

Soil Layer

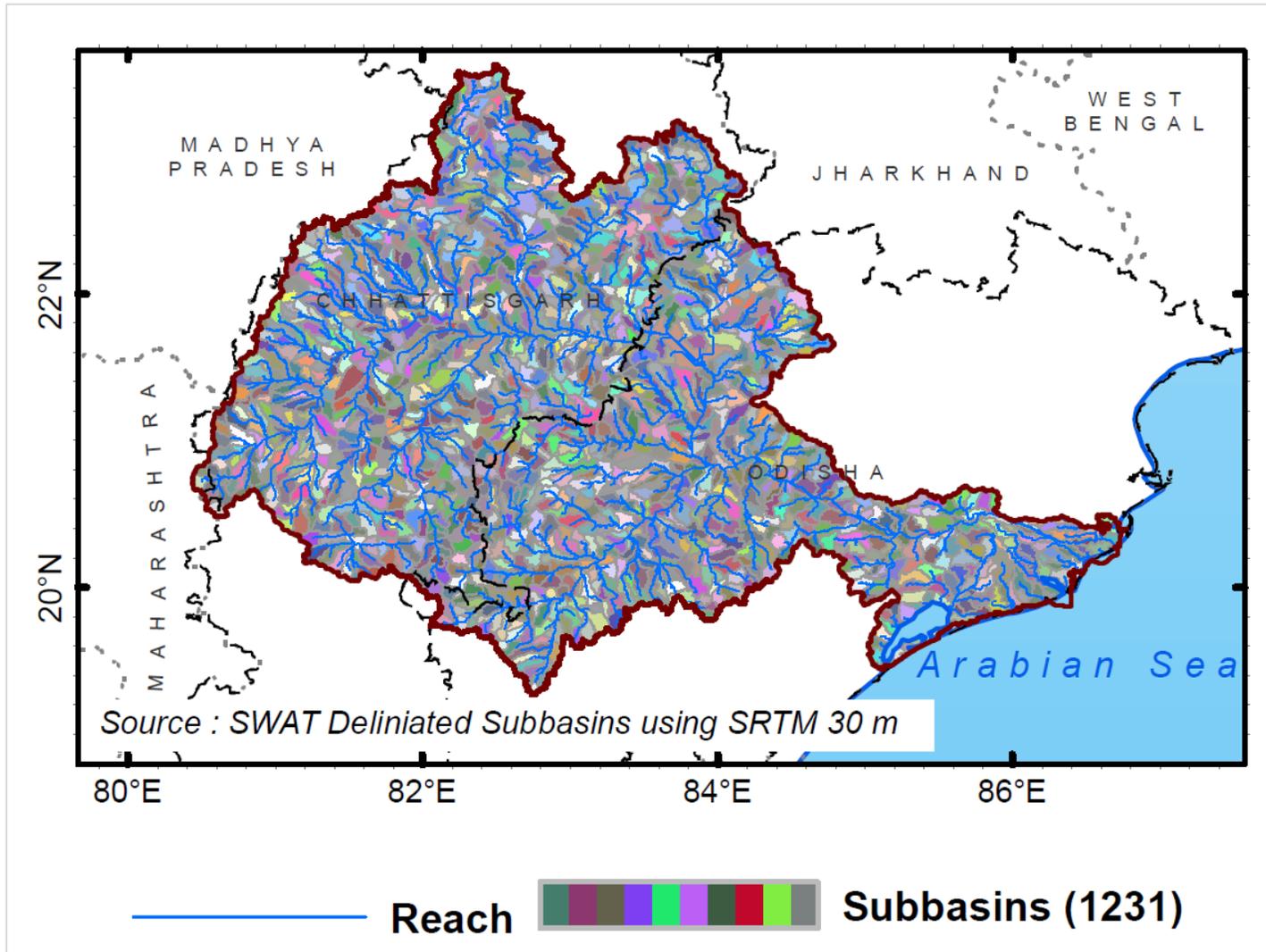


Predominantly Sandy Loam and Sandy clay loam

Source: NBSSLUP/FAO Global soil,
<http://www.lib.berkeley.edu/EART/fao.html>

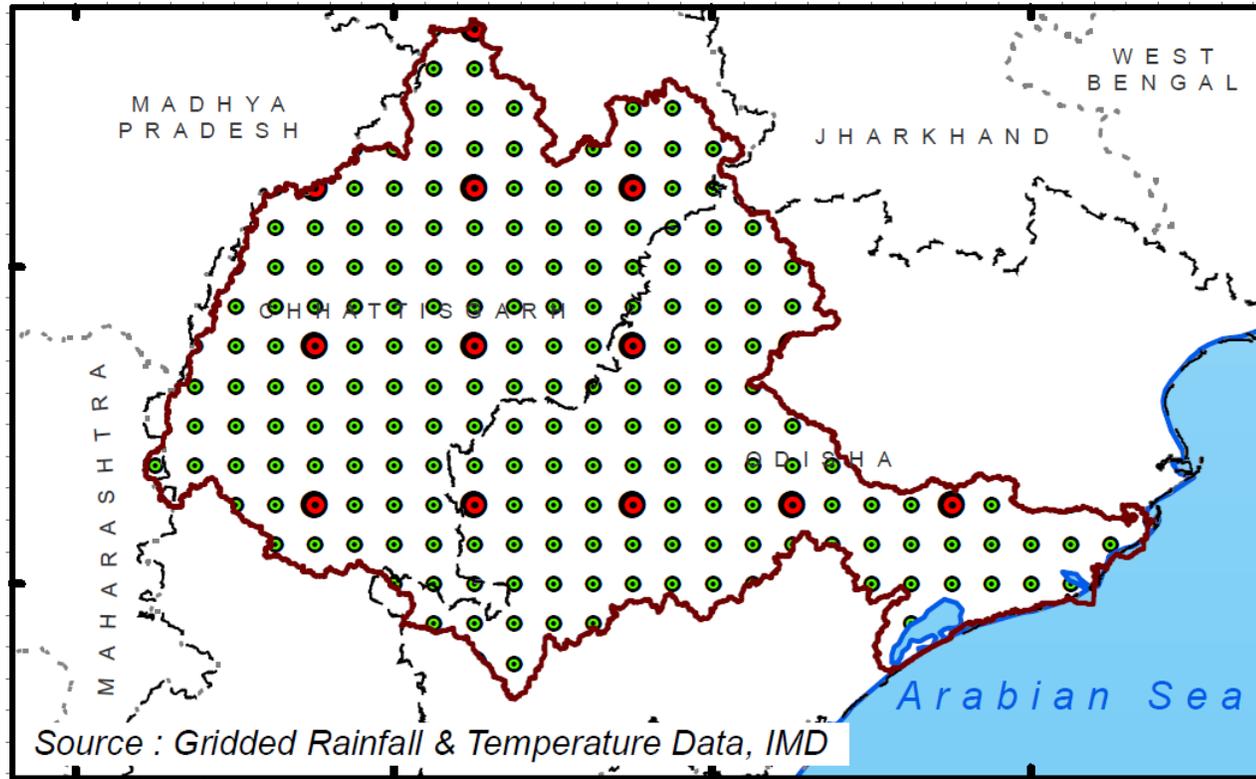
Soil Texture -Main	Area (ha)	% of Watershed Area
Clayey	697,546	4.7
Clay Loam	2,344,941	15.8
Loam	786,594	5.3
Sandy Clay Loam	2,938,597	19.8
Sandy Loam	7,732,370	52.1

Subbasin Configuration



- Threshold: 5,000 ha
- 1231 sub-basins
- HRUs: 7500
- Basin area: 1,48,414 sq. Km.

Observed Weather Station Locations



● Temperature Grids (12) ● Precipitation grids (197)

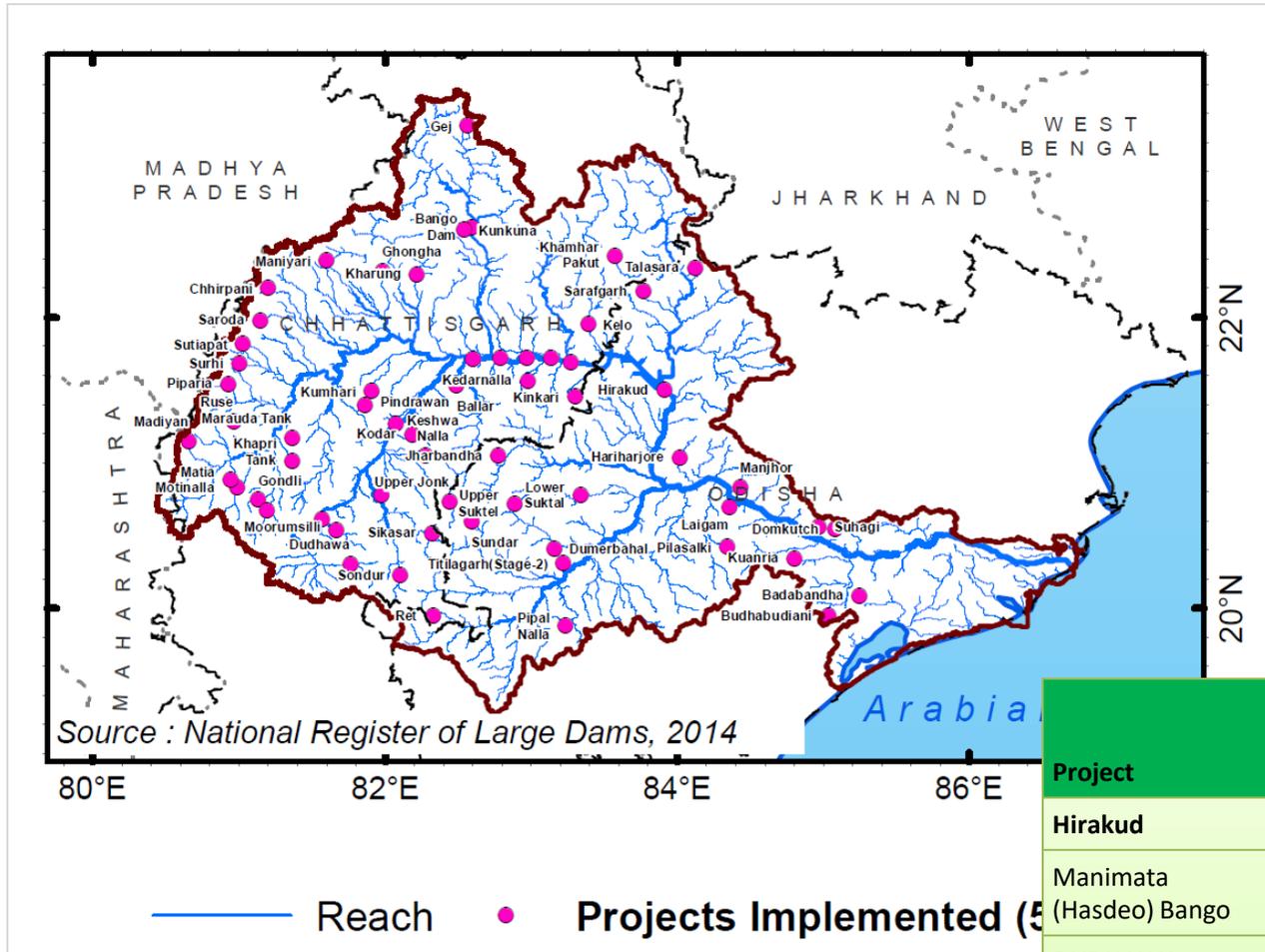
IMD gridded rainfall

- 197 grids
- Daily from 1951-2016

IMD gridded
Maximum and
minimum
temperature grids

- 12 grids
- Daily from 1951-2016

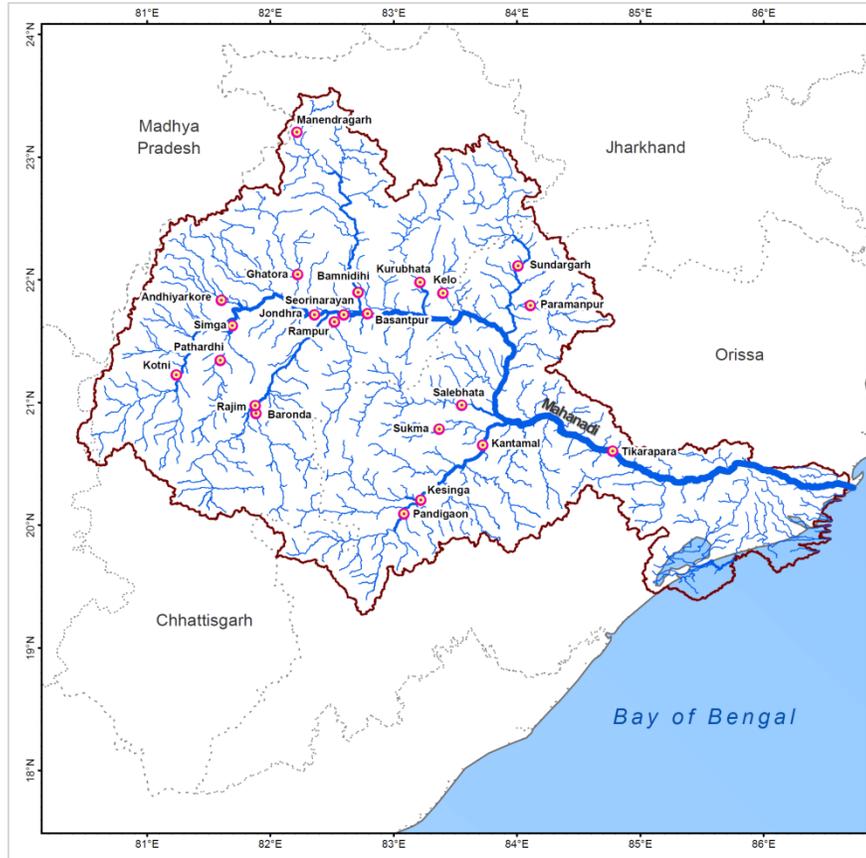
Major Projects Implemented



- 220 projects
- 75 major/medium
- 23 major projects

Project	River	Year	Gross Storage MCM	Live Storage MCM	Area at FRL km ²
Hirakud	Mahanadi	1957	8140	5820	743
Manimata (Hasdeo) Bango	Hasdeo	1990	3420	3050	188
DUDHAWA	Mahanadi	1963	289	284	45
R.S. SAGAR	Mahanadi	1979	911	767	95
SONDUR	Local	1989	198	180	24
TANDULA TANK	Tandula & Sukhanalla	1920		312	46

SWAT – Validation Locations



SWAT Validation Locations MAHANADI BASIN

Legend

- SWAT Validation Locations
- River Network

Boundaries

- Mahanadi
- - - State

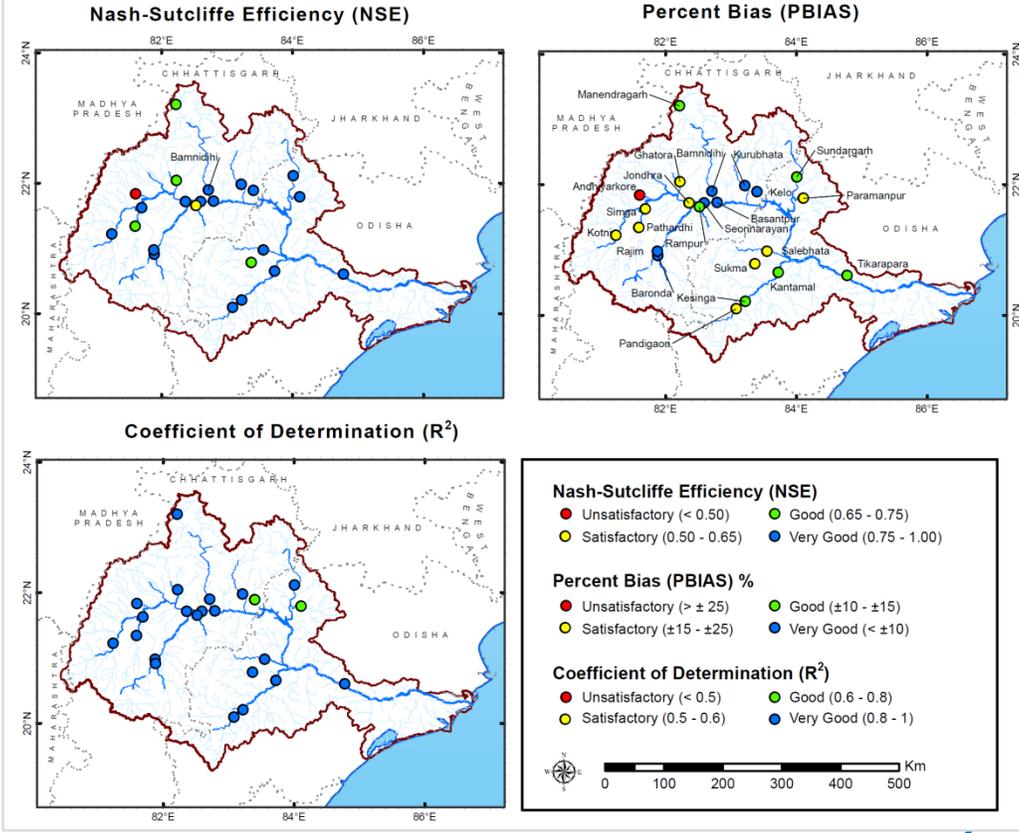
Scale: 0 to 200 Km

- 23 calibration/validation locations

S.No	Site Name	River	Drainage Area (Km ²)	Swat Subbasin	SWAT Drainage Area (km ²)	Area Difference (%)
1	Andhiyarkore	Sakri	2210	281	2197	-0.59
2	Bamnidihi	Hasdeo	9730	247	9934	2.05
3	Ghatore	Kurang	3035	225	3105	2.25
4	Kantamal	Tel	19600	647	20583	4.78
5	Kurubhata	Mand	4625	215	4835	4.34
6	Rampur	Bhedan	2920	269	3312	11.84
7	Salebhate	Trib near Tel	4650	522	4689	0.83
8	Simga	Seonath	30761	372	16970	-81.27
9	Sukma	Trib Tel	1365	617	1290	-5.81
10	Sundargarh	Ib	5870	168	5989	1.99
11	Tikarapara	Mahanadi	124450	642	128244	2.96

SWAT – Calibration

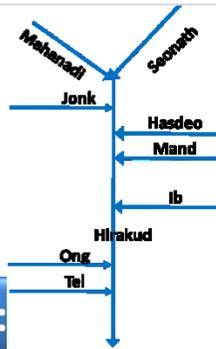
Mahanadi River Basin - SWAT Model Performance Parameters



- 23 validation locations

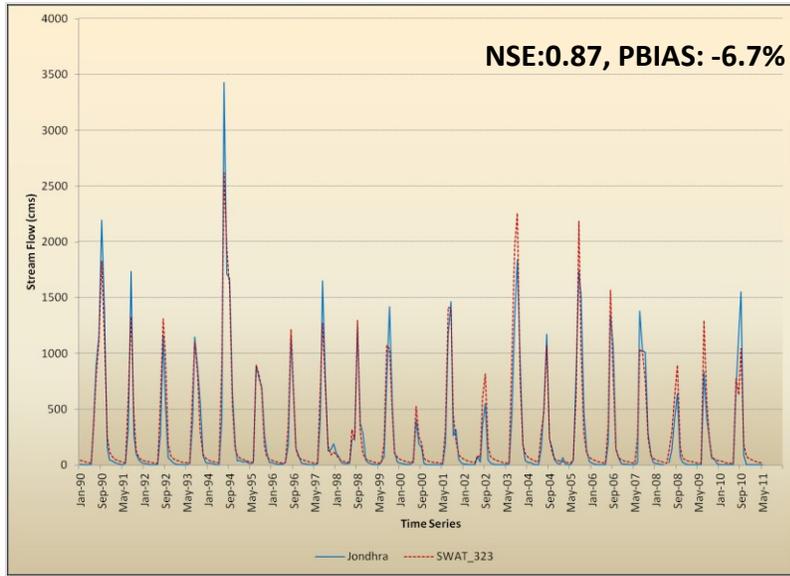
Station	River Name	PBIAS	Correlation coeff	COE/ Nash	RSR
Kotni	Seonath	-3.53	0.94	0.88	0.35
Pathardhi	Seonath	3.90	0.89	0.78	0.47
Simga	Seonath	-7.30	0.91	0.81	0.43
Andhiyarkore	Hamp	-1.33	0.88	0.75	0.50
Ghatora	Arpa	13.90	0.89	0.79	0.46
Jondhra	Seonath	-6.70	0.93	0.87	0.36
Baronda	Pairi	11.60	0.89	0.79	0.45
Rajim	Mahanadi	10.30	0.92	0.85	0.39
Rampur	Jonk	11.30	0.81	0.65	0.59
Seorinarayan	Mahanadi	6.50	0.95	0.90	0.33
Manendragarh	Hasdeo	0.40	0.76	0.33	0.82
Bamnidihi	Hasdeo	7.10	0.77	0.59	0.64
Basantpur	Mahanadi	4.60	0.95	0.91	0.33
Kurubhata	Mand	10.20	0.94	0.88	0.36
Kelo at Raigarh		-37.80	0.77	0.72	0.53
Sundargarh	Ib	3.40	0.97	0.85	0.30
Paramanpur	Bedan/Ib	18.20	0.95	0.93	0.27
Salebhata	Ong	-0.50	0.93	0.87	0.40
Pandigaon	Tel	6.90	0.95	0.90	0.33
Kesinga	Tel	-0.00	0.97	0.95	0.27
Kantamal	Tel	-2.10	0.97	0.94	0.29
Sukma	Suktel	-6.40	0.85	0.73	0.43
Tikarapara	Mahanadi	-5.70	0.95	0.91	0.33

Range	NSE	RSR	PBAIS(%) + or -
V Good	0.75 - 1.0	0.0 - 0.5	< 10
Good	0.65 - 0.75	0.5 - 0.6	10 - 15
Satisfactory	0.5 - 0.65	0.6 - 0.7	15 - 25
Unsatisfactory	<0.5	> 0.7	> 25

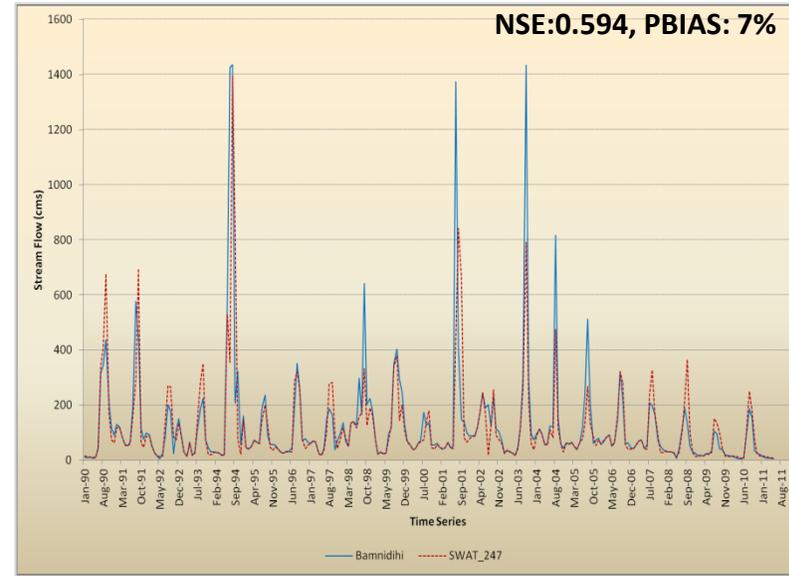


Model Calibration

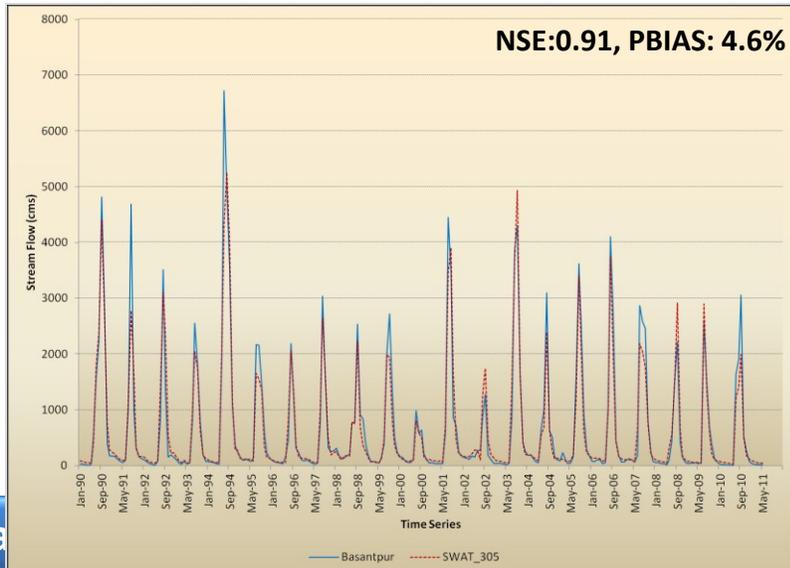
Jondhra- Seonath



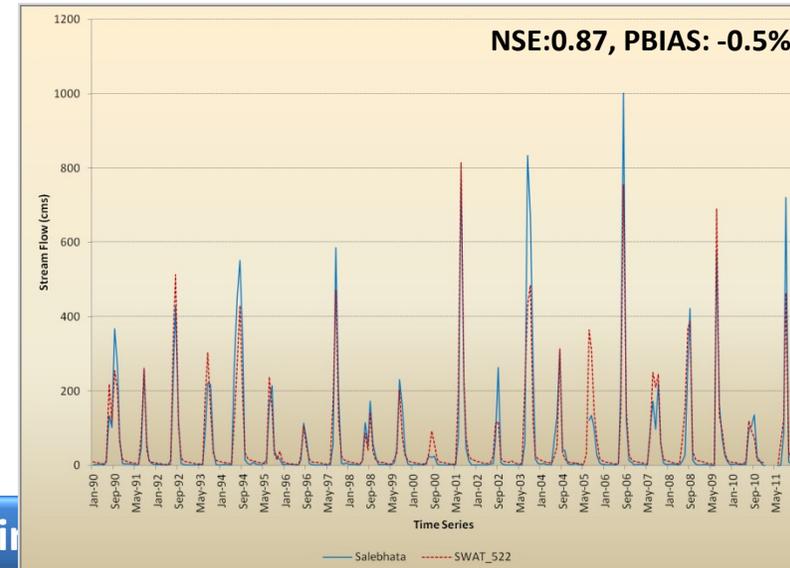
Bamnidihi – Hasdeo



Basantpur - Mahanadi



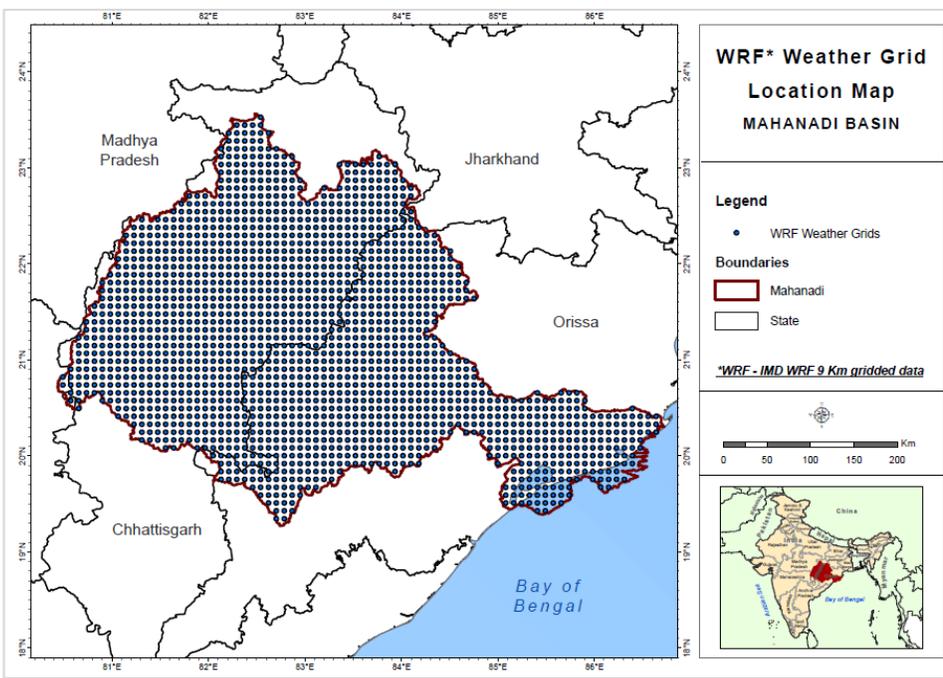
Salebhata- Ong





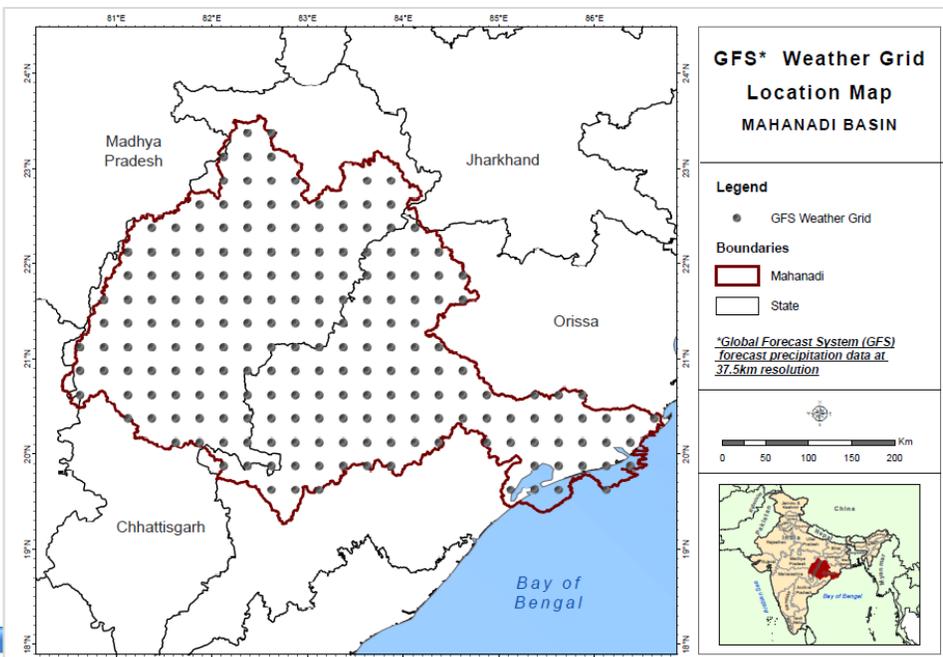
Mahanadi Basin EWS - Process

- SWAT hydrological model is used to simulate the inflow to Hirakud reservoir
 - Hydrological modelling has been carried out for the entire Mahanadi basin
 - Calibrated and validated model is currently run at daily time step to produce inflow forecast
 - NWP, Multiple source rainfall forecast data is being used instead of one source to minimise the uncertainty in inflow forecast
 - Gives range of inflows rather than one single number
 - This strategy helps in issuing forecasts without any break even if one data source becomes unavailable on some days

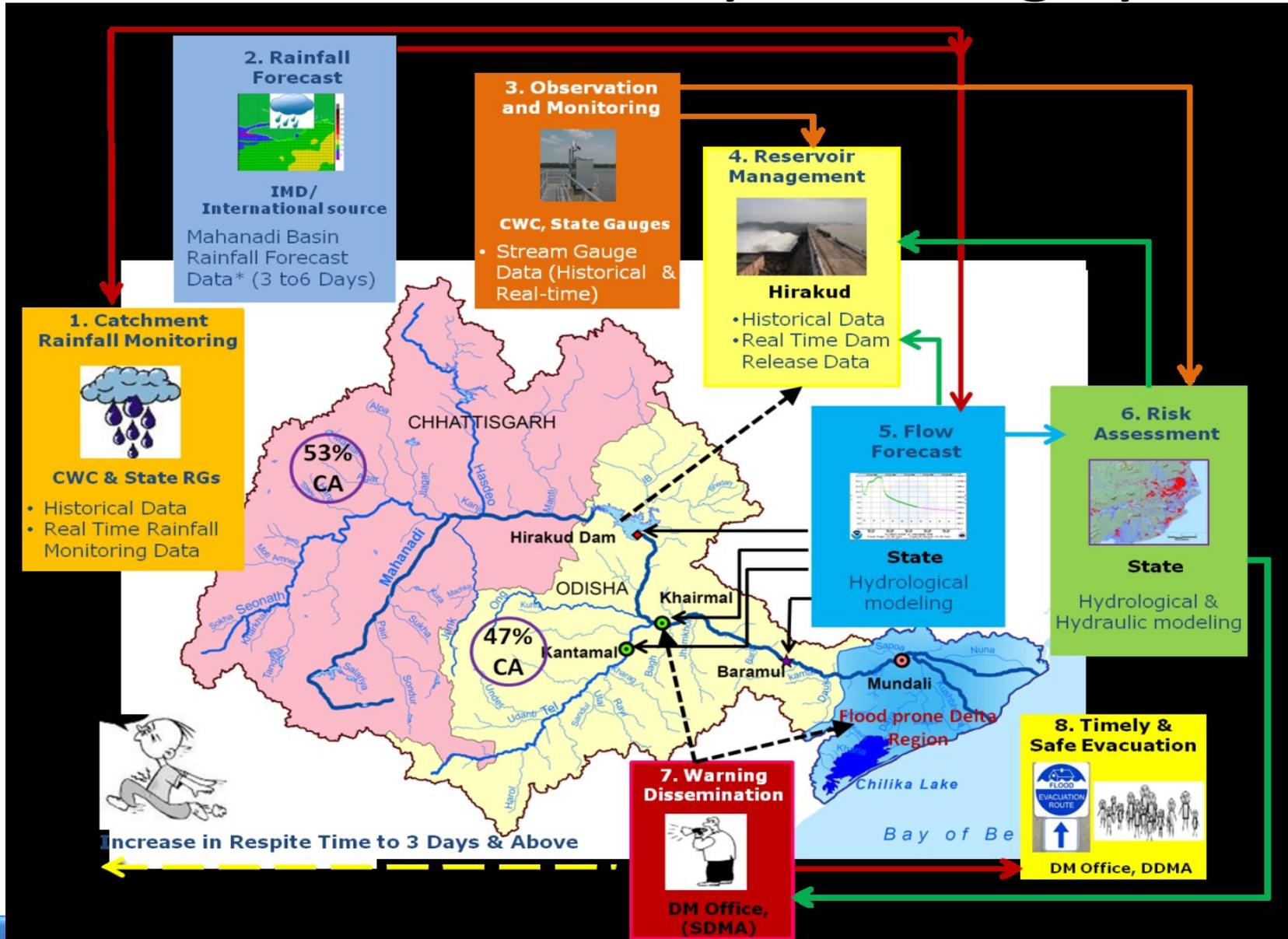


IMD Forecast

- IMD is sharing forecast directly for 2 models
- WRF Model
 - 9 km resolution
 - Daily rainfall
 - ftp transfer
- GFS Model
 - 12.5 km resolution
 - Daily rainfall
 - ftp transfer
- NOAA GFS Model
 - 37.5 km resolution
 - Daily rainfall
 - ftp transfer



Mahanadi Basin Early Warning System

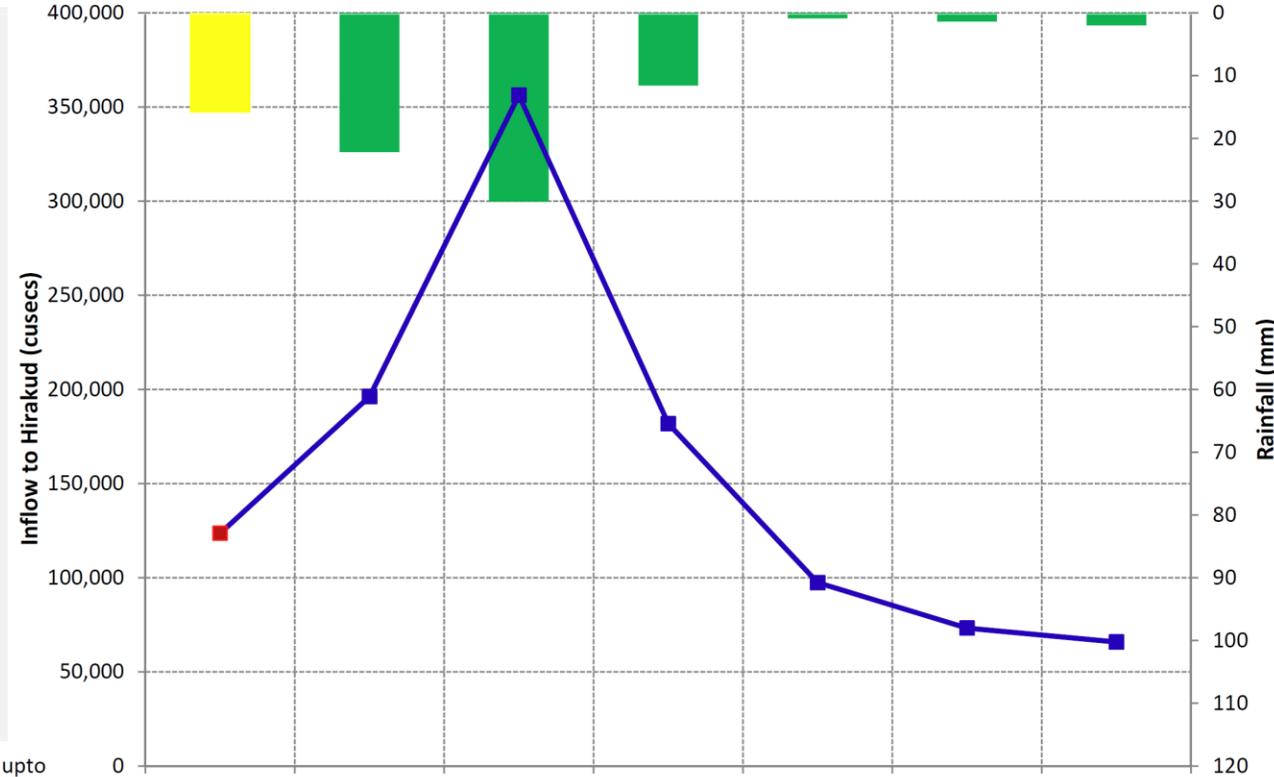
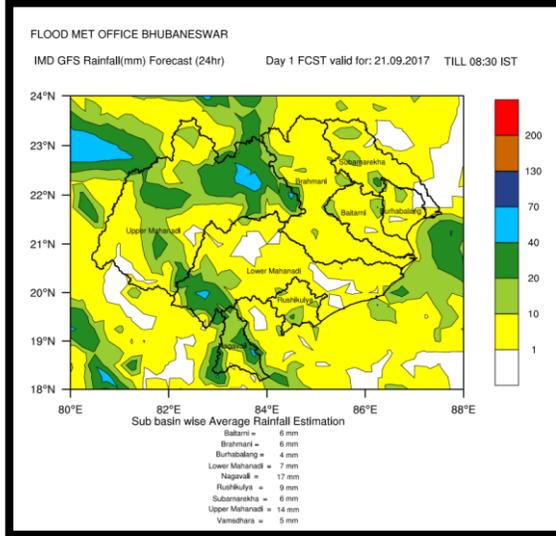


Forecast Issued – IMD GFS

Hirakud Reservoir Inflow (cusecs) Forecast using IMD GFS Rainfall Forecast Valid till 25 September 2017

Developed for DoWR, Odisha
INRM Consultants, New Delhi

Caveat
Simulated using SWAT Hydrological Model
Using Rainfall forecast from INDIA METEOROLOGICAL DEPARTMENT, NWP models.
Limitations in Model calibration:
Observed Rainfall data from Odisha



	19-Sep-17	20-Sep-17	21-Sep-17	22-Sep-17	23-Sep-17	24-Sep-17	25-Sep-17
Yellow bar: Average Catchment observed rainfall upto Hirakud on 19-09-2017	15.8						
Green bar: Average Catchment Rainfall upto Hirakud (IMD GFS 25 Km rainfall forecast)	15.9	22.2	30.1	11.6	0.9	1.4	2.0
Blue line: Inflow Forecast in cumecs using IMD GFS 25 Km rainfall forecast Valid till 25 September 2017	123,636.7	196,278.9	356,325.0	181,870.6	97,468.5	73,313.3	65,932.5

Simulated using SWAT Hydrological Model

IMD GFS: Global Forecast System 25 KM RESOLUTION)



Benefits for Dams & Hydropower



- Early warning, better scheduling, improved safety and optimized storage.
- Supports ecological flows, sediment management and drought planning.



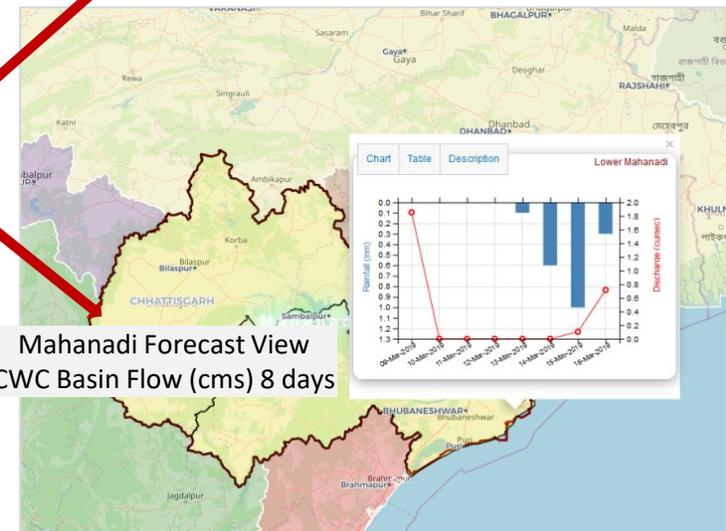
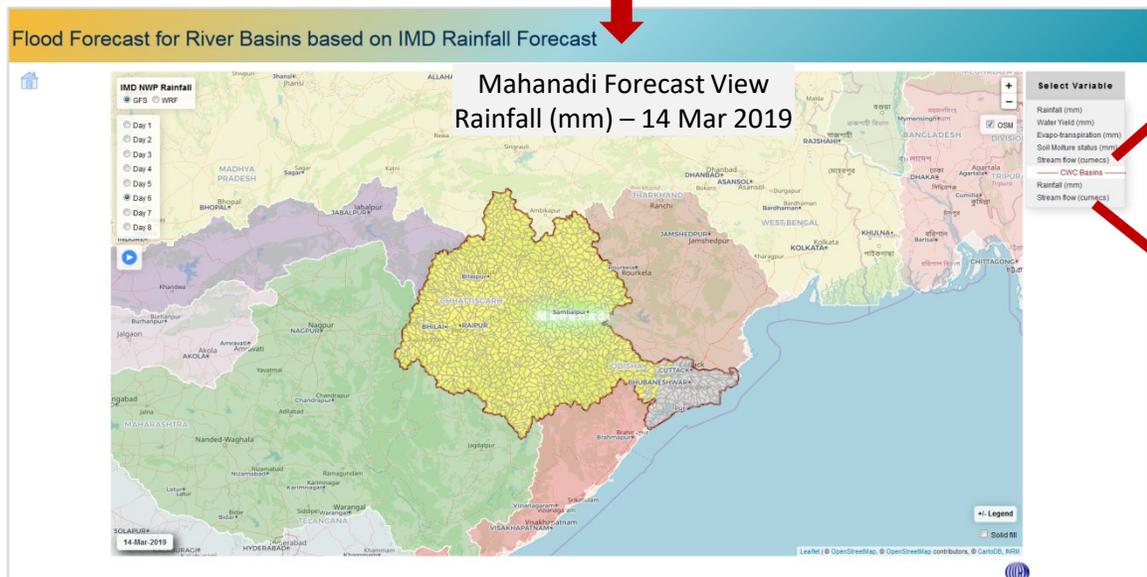
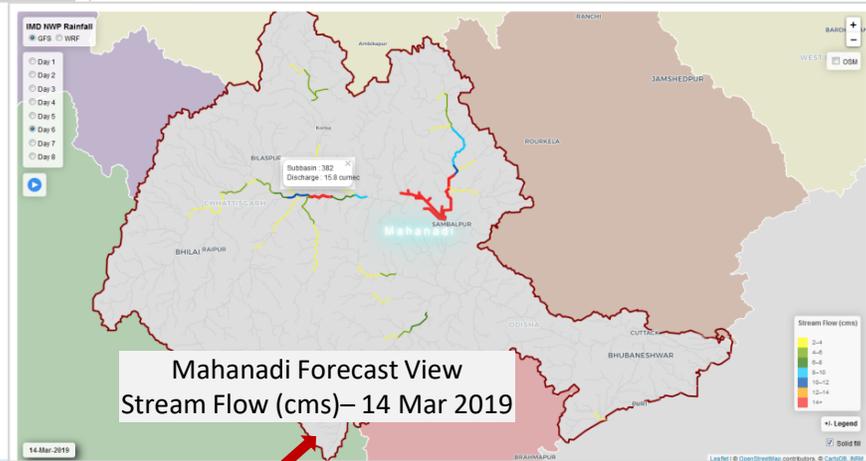
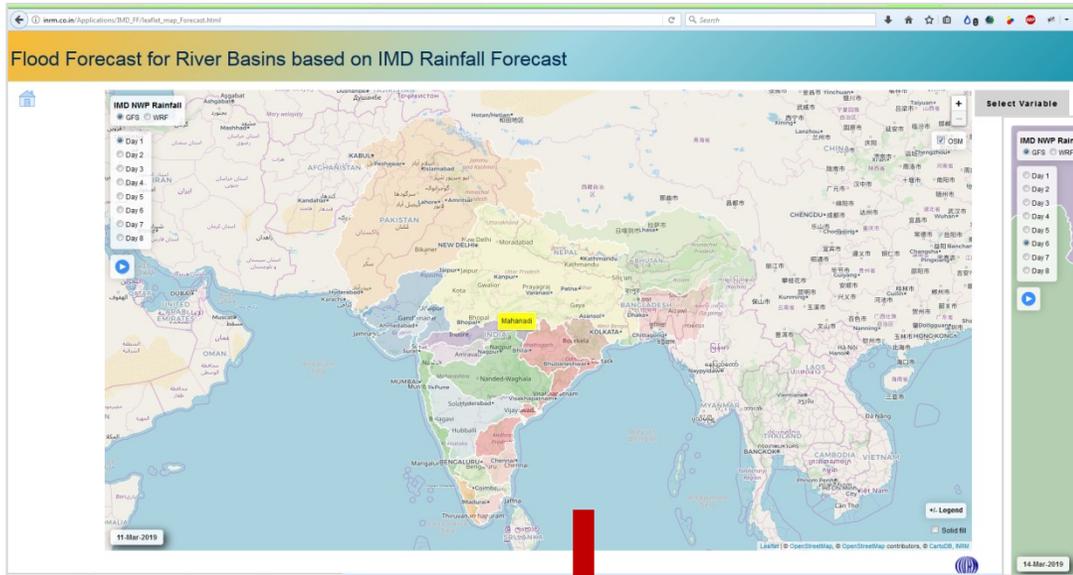
National-Scale Modelling Framework



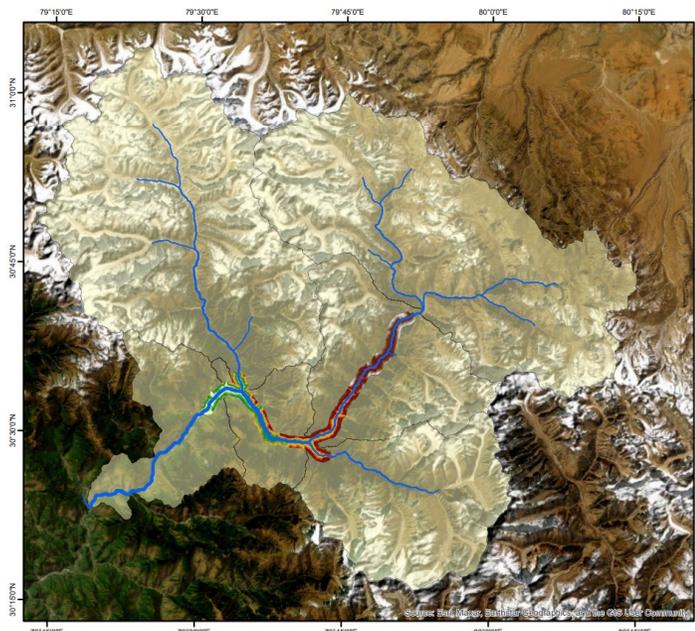
https://inrm.co.in/Applications/IMD_FF/login.php

- Developed by INRM Consultants using the SWAT hydrological model.
- Covers all 18 major river basins of India.
- Each basin divided into sub-basins and HRUs.
- Calibrated using observed CWC discharge data.
- Web based Public-domain portal provides maps, graphs and basin-wise forecasts.

Real-time Stream Flow Forecast Website



Flood Forecasting & Early Warning System (Tapovan) Riverine



Catchment Area (Contributing Area)

Legend

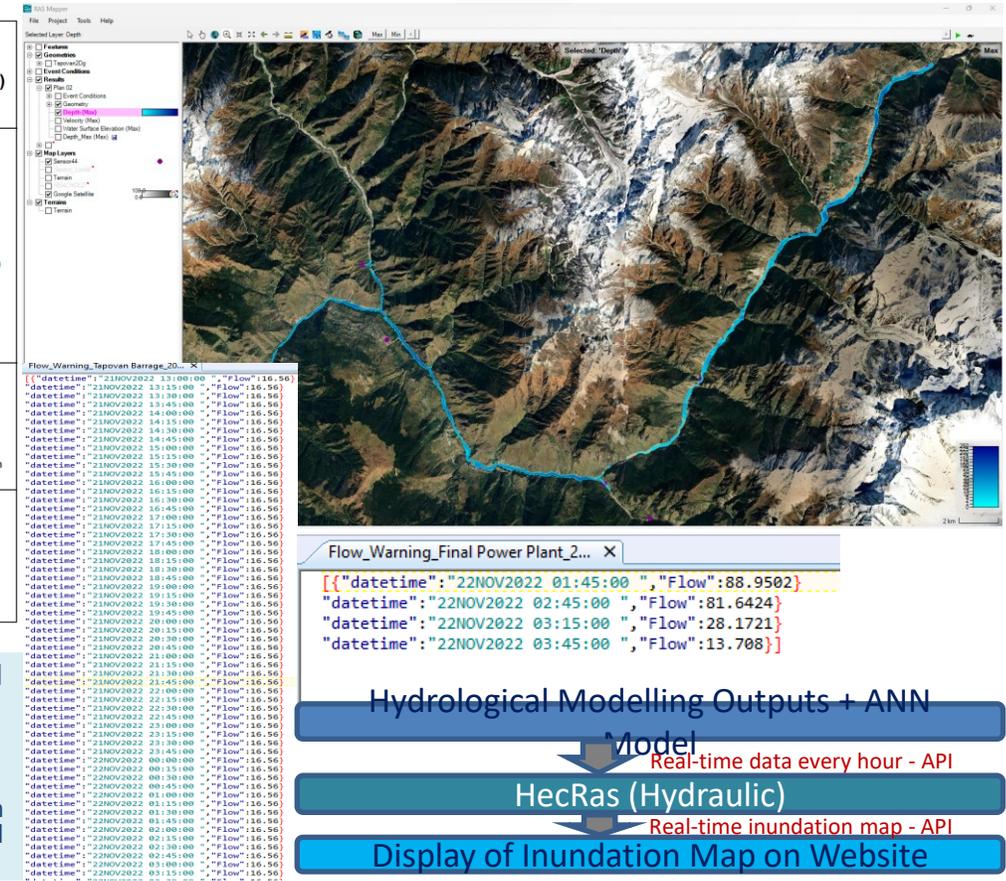
- Reach
- Subbasin

Digital Elevation Model (m)

High : 3672.03
Low : 1237.05

0 3 6 12 18 24 Km

INRM Consultants Pvt. Ltd.



datetime	Flow
"21NOV2022 13:00:00"	"Flow":16.56
"21NOV2022 13:15:00"	"Flow":16.56
"21NOV2022 13:30:00"	"Flow":16.56
"21NOV2022 13:45:00"	"Flow":16.56
"21NOV2022 14:00:00"	"Flow":16.56
"21NOV2022 14:15:00"	"Flow":16.56
"21NOV2022 14:30:00"	"Flow":16.56
"21NOV2022 14:45:00"	"Flow":16.56
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"22NOV2022 02:45:00"	"Flow":16.56
"22NOV2022 03:00:00"	"Flow":16.56
"22NOV2022 03:15:00"	"Flow":16.56

➤ **Coupled hydrological and Hydrodynamic modelling / Artificial Neural Network Model (ANN model)**

- ❑ [Increases warning time](#)
- ❑ Faster processing
- ❑ Can use forecasted rainfall and predict probable flood well in advance (7 or 3 days warning), which can be revised daily based on fresh forecast

Hydrological Modelling Outputs + ANN Model

↓ Real-time data every hour - API

HecRas (Hydraulic)

↓ Real-time inundation map - API

Display of Inundation Map on Website

MoU has been signed with BWI – Pioneer in AI and creating virtual station

Virtual Station deliver hydrological data digitally by leveraging various data sources (in-situ, satellite, meteorological, model-based, etc.).

Use cases

- Provision of forecasts (flow rates & water levels) up to 10 days ahead (trend-based)
- Data access via API or user interface

Key benefits

- Flexible location on the hydrographic network
- Instant deployment
- Remote operation
- Continuous improvement



Conclusions

- We must move beyond conventional engineering approaches and adopt integrated, adaptive, and ecosystem-sensitive frameworks
- Sustainable dam and hydropower development must balance structural safety, energy efficiency, and water security with environmental flows and social equity
- Mainstreaming climate risk assessments, using high-resolution hydrological and climate models, and adopting dynamic reservoir operation rules that can respond to uncertainty



Thank You

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- www.inrm.co.in