Project Title:
Impact Assessment of Climate Change on Hydro-meteorological processes and Water Resources of Mahanadi River Basin

[MoWR Administrative Approval Ref. No. : 16/22/2016-R&D/4015-4032 Dated: 07.11.2016]

IISc Scheme Ref No.: 28/1/2016-R&D/228-245 Dated: 08.02.2018

Duration of Project: 3 years (07.03.2018 to 06.03.2021)

Investigators:

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&

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Objectives of the project

1. Trend analysis of the observed meteorological and hydrologic data and exploration of possible causes for trend (if evident).

2. Modelling hydrological processes in Mahanadi basin utilizing historical data for baseline period.

3. Establishing relationships between components of hydrological cycle (i.e., water balance components) in the basin for the current (historical) scenario using baseline data.

4. Identification of hydro-meteorological extremes (including extreme rainfall, floods, and droughts) based on the base line data, and developing equations to estimate their magnitude corresponding to various frequencies at gauged and ungauged target locations (hot spots) in the river basin.

5. Assessment of changes in relationships between the components of hydrological cycle (i.e., water balance components) in the river basin for future climate change scenarios using downscaled projections on meteorological variables.

6. Assessment of impact of climate change on water availability at critical gauged as well as ungauged locations (hot spots) in the basin in terms of change in flow duration curves.

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

Objectives of the project

7. Assessment of changes in irrigation water demands corresponding to various climate change scenarios.
8. Development of operating policies for the Hirakud reservoir corresponding to the current and climate change scenarios.
9. Assessment of impact of climate change on magnitude and frequency of meteorological and hydrological extremes in the basin at the identified hot spots.
10. Trend analysis of the observed sediment data.
11. Establishing a relationship between the suspended and bed sediment transport and the discharge in the river utilizing the past data.
12. Assessment of trend in the annual sediment yield of the Mahanadi river for future climate change scenarios.
13. Assessment of trend in the variation of the reservoir capacity of the Hirakud dam for the current and future scenarios.
14. Assessment of uncertainties in the impacts associated with the use of various GCMs, climate change scenarios and hydrological models.
15. Framing recommendations for adaptation measures/options to mitigate adverse impacts of climate changes in Mahanadi basin.

Mapping of Milestones/activities

Sl. No	Milestone/ Activity	Time in Months											
		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
1	Coordination Meetings to commence the project	▬											
2	Recruitment of Staff & Procurement of Equipment	▬											
3	Review of literature and detailed specification of research approach	▬	▬										
4	Procuring topographic, meteorologic, hydrologic and sediment data	▬	▬	▬									
5	Compilation and base line analysis of data			▬									

(to be undertaken by all the Investigators)

Mapping of Milestones/activities

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		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
6	Trend analysis of observed meteorological, hydrological and sediment data			■	■								
7	Analysis on hydrometeorological Extremes based on the base line data					■	■	■					
8	Modelling hydrological processes in Mahanadi basin for baseline (historical) period				■	■	■	■					
9	Modelling sediment transport in Mahanadi basin for baseline period				■	■	■	■					

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

Mapping of Milestones/activities

Sl. No	Milestone/ Activity	Time in Months											
		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
10	Running future projections of meteorological variables through the developed hydrological models						▬	▬	▬				
11	Assessing impact of climate change on water availability at hot spots							▬	▬				
12	Running future projections of streamflows through sediment transport model								▬	▬			
13	Assessment of impact of climate change on hydrometeorological extremes									▬	▬		

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

Mapping of Milestones/activities

Sl. No	Milestone/ Activity	Time in Months											
		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
14	Determining future projections of irrigation water demands at Hirakud reservoir for various climate change scenarios, and the corresponding operating policies									▬	▬	▬	
15	Assessing implication of historical and future sediment load on capacity of Hirakud reservoir										▬	▬	
16	Final Report Preparation												▬

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

Work Progress on Milestones/activities

Project start date: 07.03.2018

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		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
1	Coordination Meetings to commence the project												
2	Recruitment of Staff & Procurement of Equipment												
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4	Procuring topographic, meteorologic, hydrologic and sediment data												
5	Compilation and base line analysis of data												

(to be undertaken by all the Investigators)

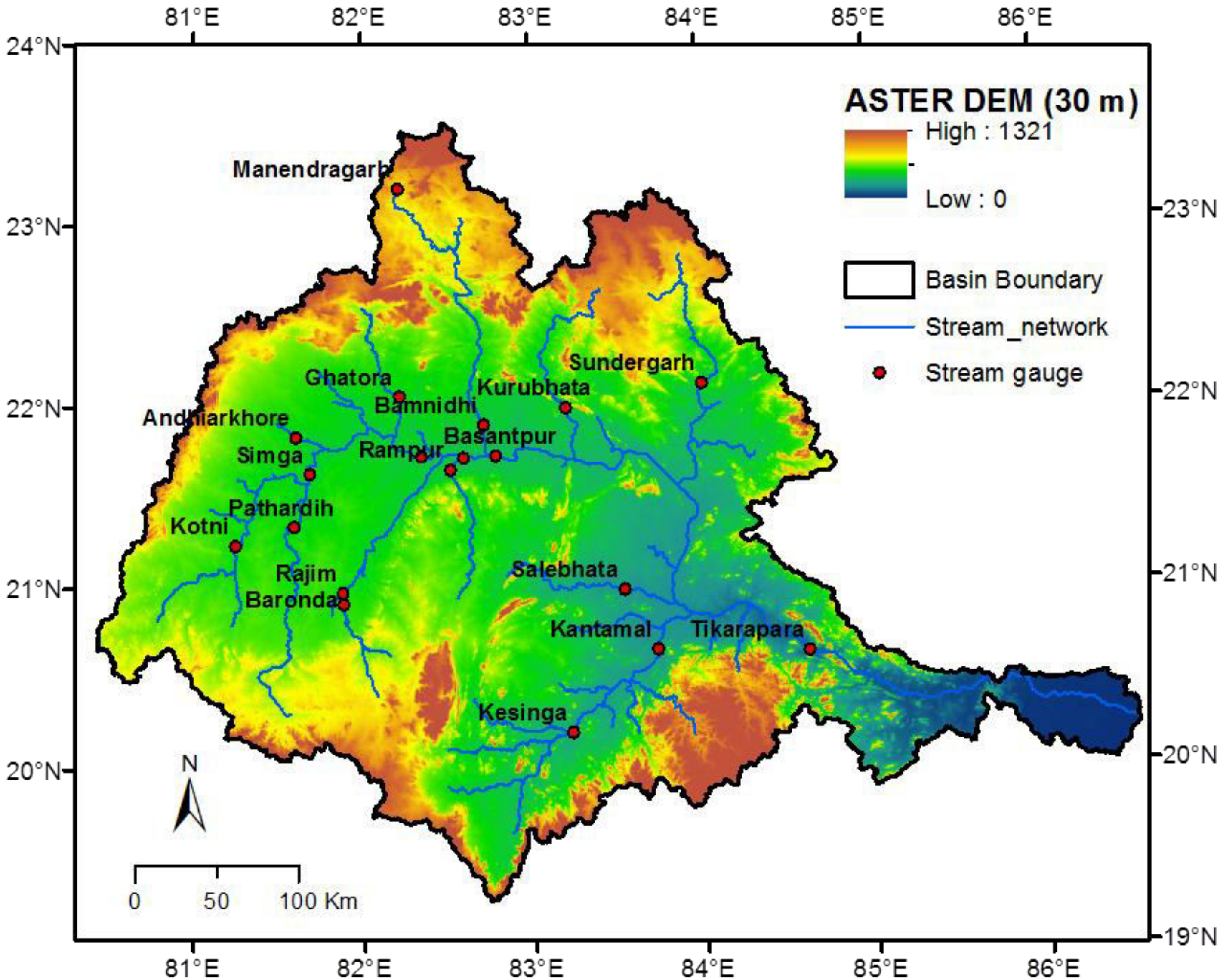
Work Progress (Technical) : Literature review

Literature review was conducted to update the information gathered *a priori* on the identified research objectives of the project.

Further Scope

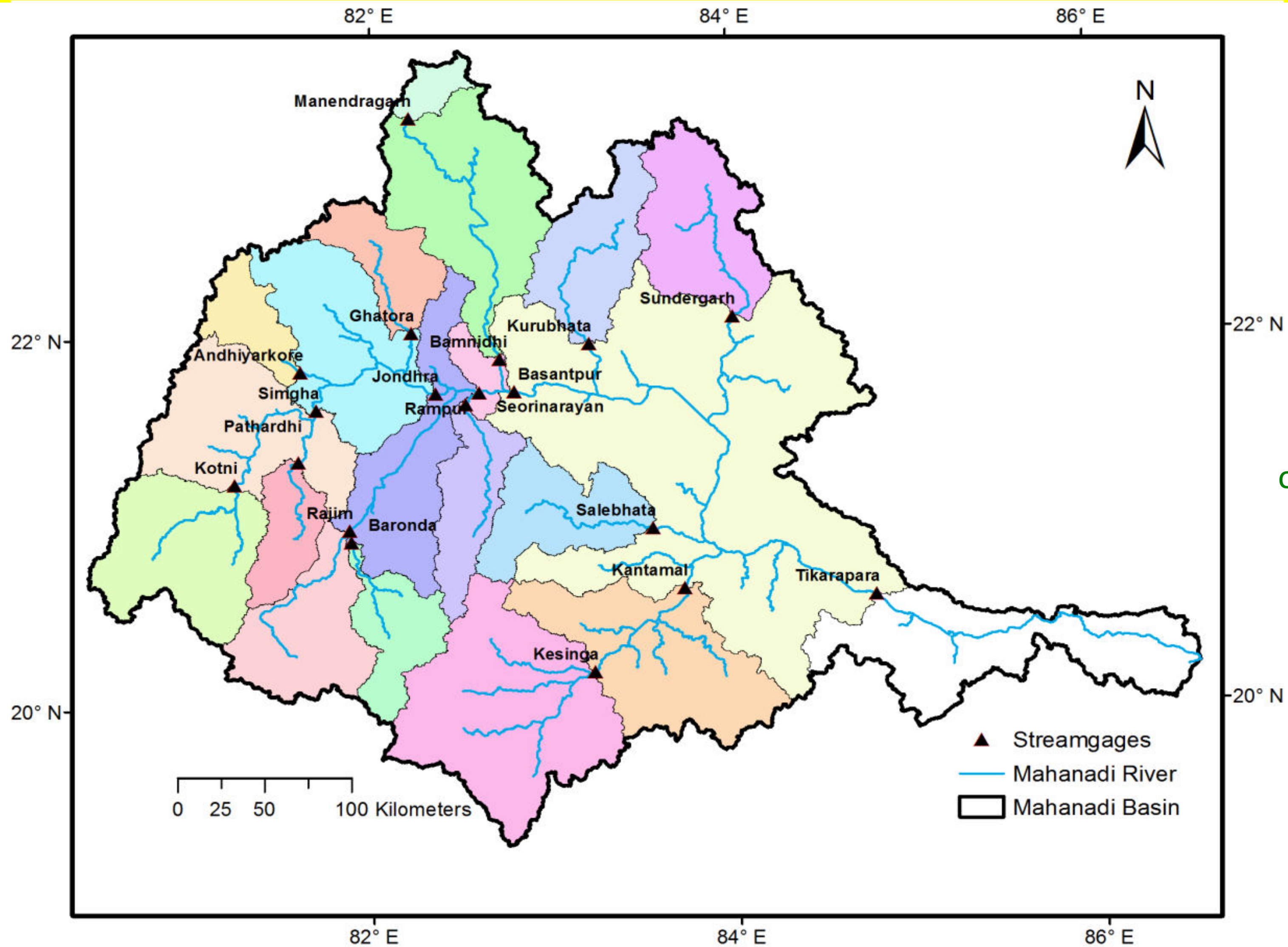
- ✓ *Multiple* uncertainties have to be accounted in downscaling and rainfall-runoff modelling
- ✓ Investigating the temporal dependence between (i) different characteristics of floods, and (ii) different types of droughts for future climate change scenarios
- ✓ Better strategies to account for lakes and wetlands in rainfall-runoff models
- ✓ Scope for using satellite data to estimate air temperature, precipitation, evapotranspiration, soil moisture

Work Progress (Technical): Delineation of river basin and stream network



Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

Work Progress (Technical): Delineation of watersheds



Result based on ASTER 30m

- DEMs considered: SRTM, ASTER
- Estimated catchment areas were found to be sufficiently close to those available with CWC, except for catchments of two gauges located at Rampur and Simga

S.No.	Catchment of gauge	Catchment area (km^2)			R-bias (%)	
		SRTM (90m)	ASTER (30m)	CWC estimate	SRTM (90m)	ASTER (30m)
1	Manendragarh	1017.17	1016.18	1100	-7.53	-7.62
2	Andhiarkhore	2133.38	2179.60	2210	-3.47	-1.38
3	Patherdih	2494.70	2481.91	2511	-0.65	-1.16
4	Ghatora	2935.10	3076.332	3035	-3.29	1.36
5	Baronda	3213.44	3205.76	3225	-0.36	-0.60
6	Rampur	3436.02	3433.51	2920	17.67	17.59
7	Salebhata	4632.10	4574.69	4650	-0.38	-1.62
8	Kurubhata	4763.69	4822.36	4625	3.00	4.27
9	Sundergarh	6061.67	5974.34	5870	3.27	1.78
10	Kotni	7063.33	7050.28	6990	1.05	0.86
11	Rajim	8494.70	8419.36	8760	-3.03	-3.89
12	Bamnidhi	9878.19	9869.70	9730	1.52	1.44
13	Kesinga	12004.34	11929.62	11960	0.37	-0.25
14	Kantamal	20237.98	20535.30	19600	3.25	4.77
15	Jondhra	29901.00	33086.59	29645	0.86	11.61
16	Seorinarayan	48265.56	47754.02	48050	0.45	-0.62
17	Basantpur	58647.15	58750.02	57780	1.50	1.68
18	Tikarapara	127415.20	127118.8	124450	2.38	2.14
19	Simga	16790	20668	30761	-45.42	-32.81

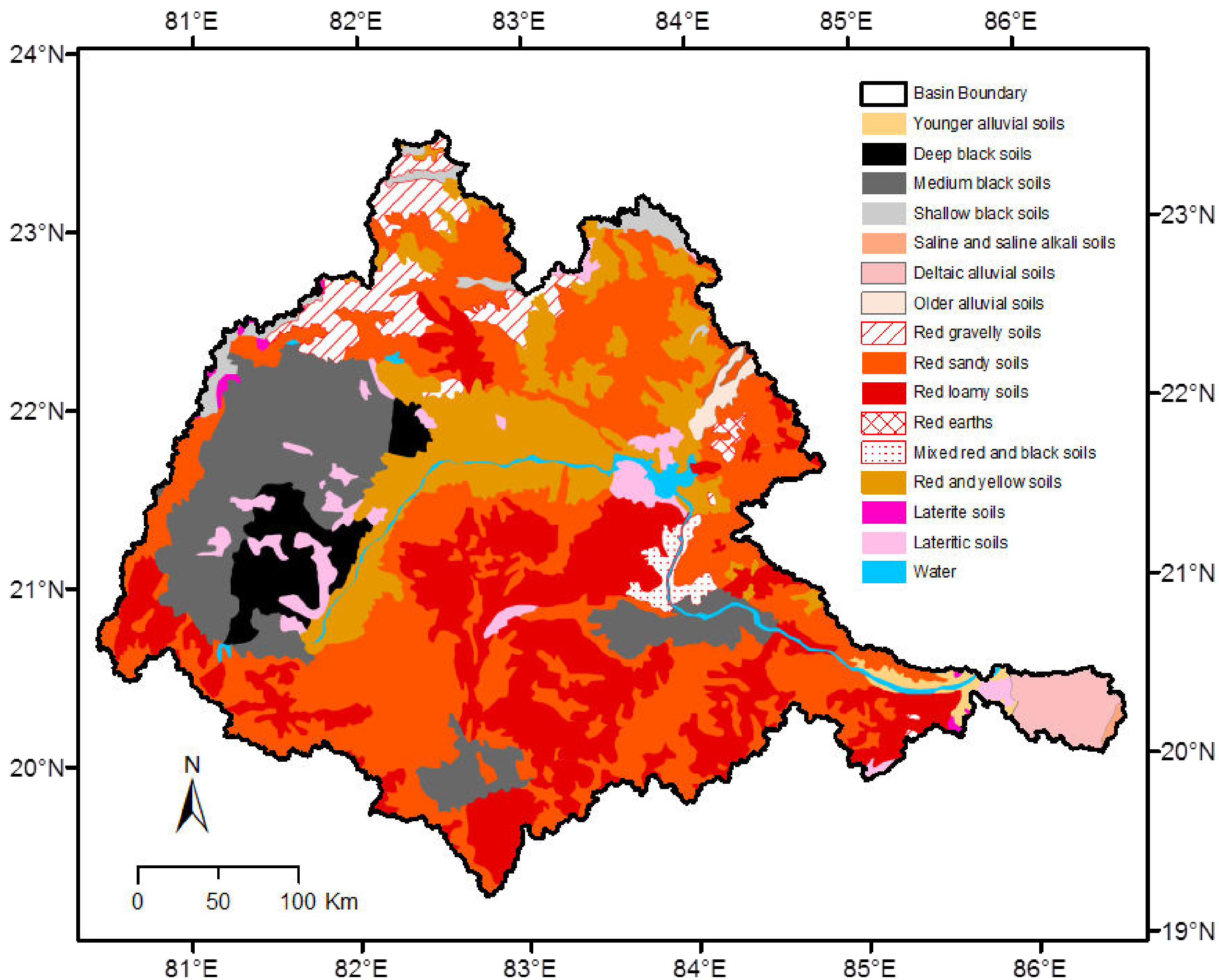
Flow estimates (in Mm^3) for different gauges in Mahanadi basin

Month	Andhiyarkore	Bamnidihi	Baronda	Basantpur	Ghatora	Jondhra	Kantamal	Salebhata	Seorinarayan	Simga
January	6.29	104.79	2.31	207.24	10.85	51.62	103.88	5.21	81.86	28.77
February	4.95	79.78	1.77	164.06	5.63	39.16	70.64	6.12	63.47	22.76
March	3.17	73.61	1.00	127.69	2.88	21.14	59.17	5.00	31.83	12.23
April	1.63	74.17	0.42	97.11	1.68	10.64	53.34	3.07	19.85	8.40
May	1.11	72.17	1.12	78.21	1.40	8.68	81.79	2.12	15.83	7.62
June	16.07	265.46	63.73	795.18	35.60	238.43	476.66	78.44	568.05	148.54
July	59.66	1027.36	280.31	4329.57	190.95	1622.82	2203.37	440.92	3497.09	941.48
August	90.18	1403.26	513.58	7667.34	295.40	2852.43	3596.50	785.97	5606.02	1757.70
September	89.01	883.87	328.90	5209.28	256.62	2263.74	2495.13	493.09	4196.45	1298.04
October	32.65	269.94	83.84	1792.97	71.38	776.24	829.14	102.84	1482.26	470.01
November	13.03	150.19	16.38	603.82	20.41	218.80	363.18	23.90	421.70	117.81
December	8.51	134.36	4.93	293.96	11.49	75.84	180.65	5.40	132.44	42.12
Annual	326.27	4538.97	1298.31	21366.43	904.29	8179.52	10513.46	1952.06	16116.86	4855.46

Month	Kesinga	Kotni	Kurubhata	Manendragarh	Pathardhi	Rajim	Rampur	Sundargarh	Tikarapara
January	67.88	4.05	33.42	4.51	3.12	5.72	2.49	36.11	865.27
February	58.61	4.03	18.50	3.43	3.84	4.49	1.70	18.17	759.29
March	59.44	0.54	10.41	3.26	1.73	2.85	1.18	9.95	822.03
April	57.66	0.12	3.80	1.59	1.57	1.96	0.96	4.69	801.64
May	85.57	0.22	4.00	0.09	2.23	2.97	0.38	5.76	785.49
June	416.53	83.90	114.77	24.28	29.45	119.40	60.21	214.86	1661.89
July	1453.99	382.97	570.15	91.53	236.96	583.87	311.15	838.07	8770.42
August	2262.82	743.72	745.11	96.68	381.23	1136.26	523.80	933.89	15566.34
September	1441.17	420.87	581.95	80.07	250.76	719.88	335.21	802.69	11603.65
October	520.30	147.72	171.97	25.00	96.77	206.36	76.80	227.07	3762.75
November	220.02	31.57	68.42	7.61	16.66	44.42	19.43	88.86	1537.41
December	127.54	6.68	38.83	5.95	4.16	11.18	4.15	34.42	955.70
Annual	6771.54	1826.40	2361.32	344.01	1028.48	2839.34	1337.47	3214.54	47891.88

Work Progress (Technical) : Data collected for rainfall-runoff modelling

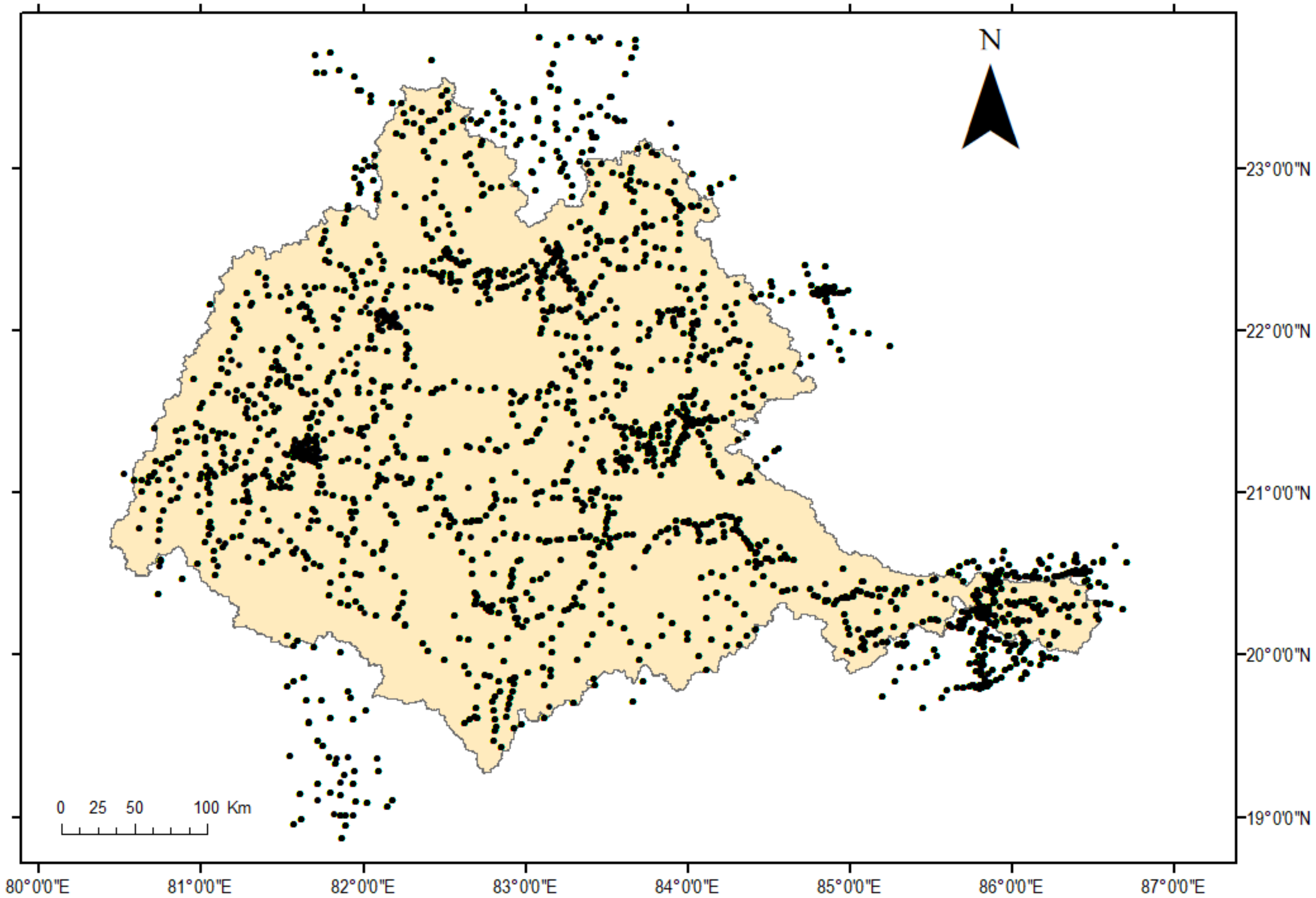
Soils in Mahanadi basin



Sources: Soils regions plate (First Edition, 1981) of National Atlas & Thematic Mapping Organization, DST, Calcutta; Research Bulletins of ICAR

ICAR: Indian Council of Agricultural Research

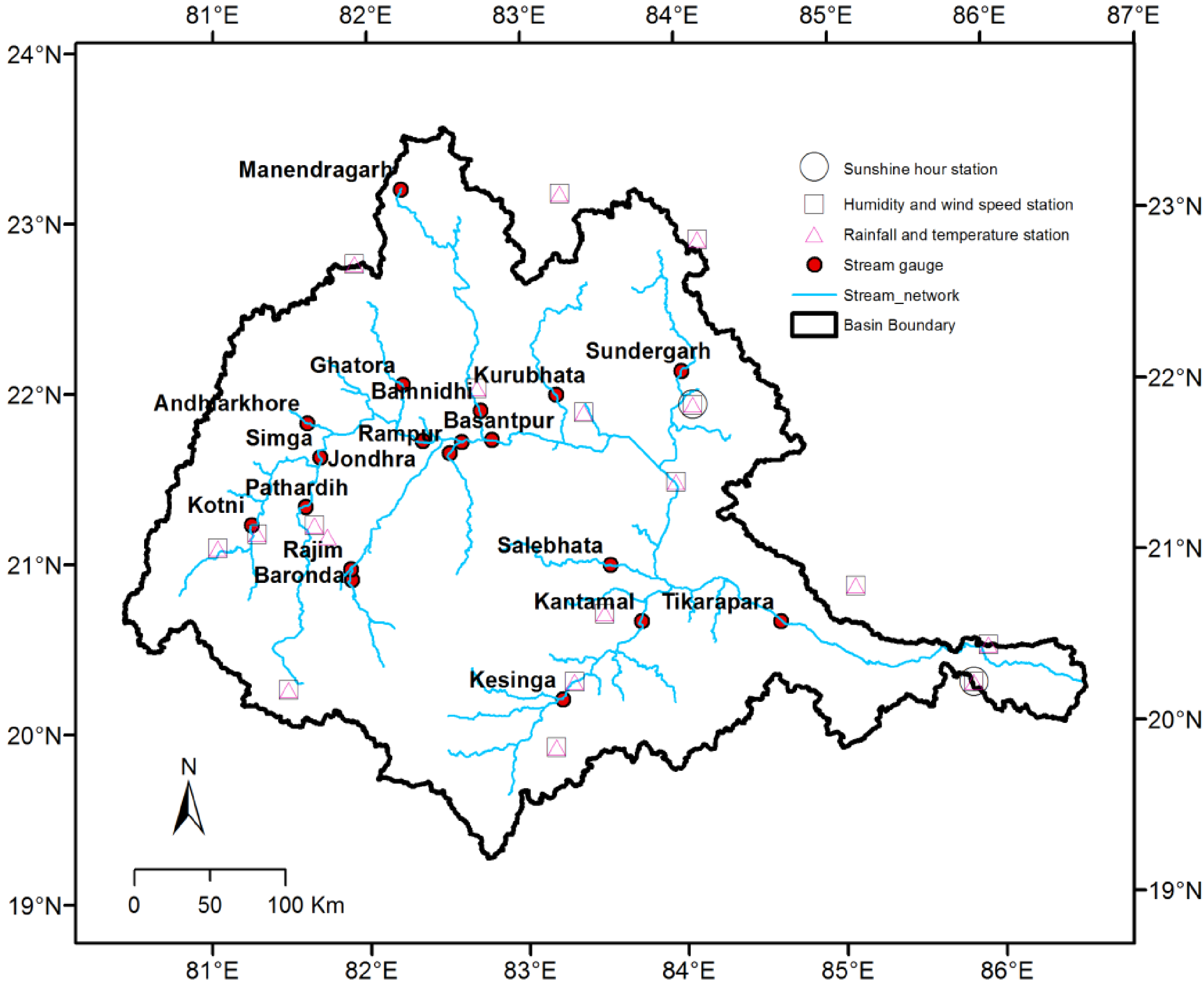
Work Progress (Technical) : Data collected for rainfall-runoff modelling



- Groundwater levels over the period 1996-2018 (source: India WRIS portal) at seasonal scale.

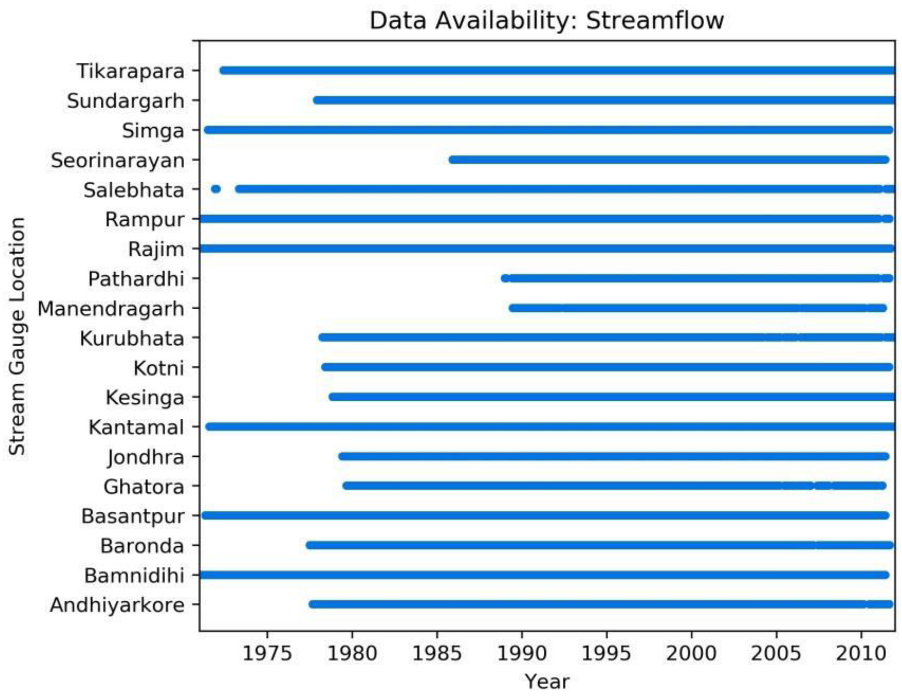
Work Progress (Technical)

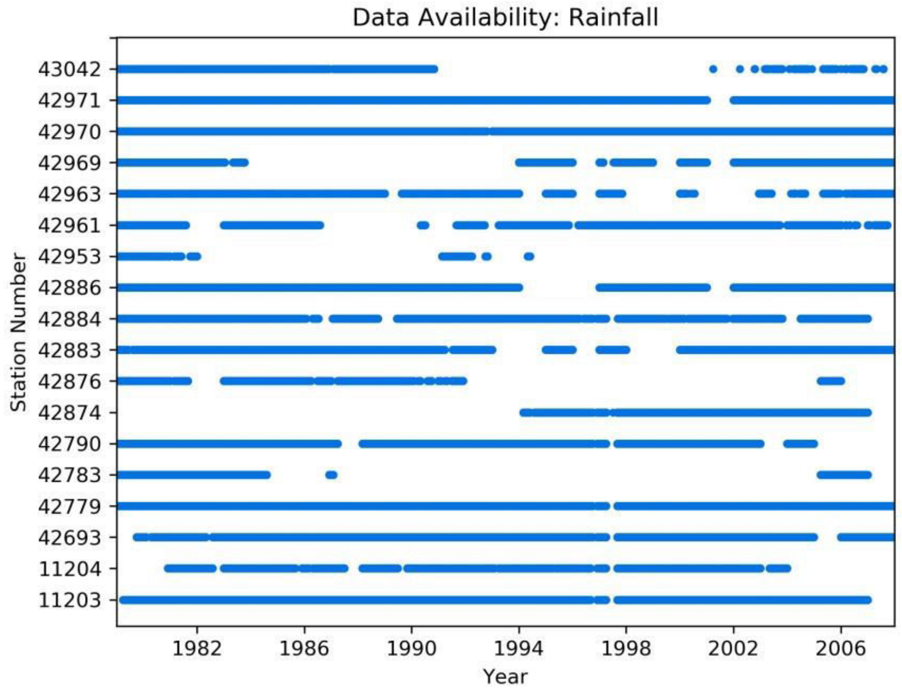
Baseline analysis was performed on IMD daily data on hydrometeorological variables, streamflows and sediment of Mahanadi river basin.



Work Progress (Technical) : Baseline analysis of hydrometeorological data

- Daily streamflows for 19 gauges (CWC)
- Daily rainfall for 18 gauges (IMD)
- Daily maximum and minimum temperatures for 18 gauges (IMD)
- Windspeed and relative humidity for 17 gauges (IMD)
- Sunshine hours for 5 gauges (IMD)





Work Progress (Technical) : Baseline analysis of hydrometeorological data

- Daily streamflows for 19 gauges (CWC)
- Daily rainfall for 18 gauges (IMD)
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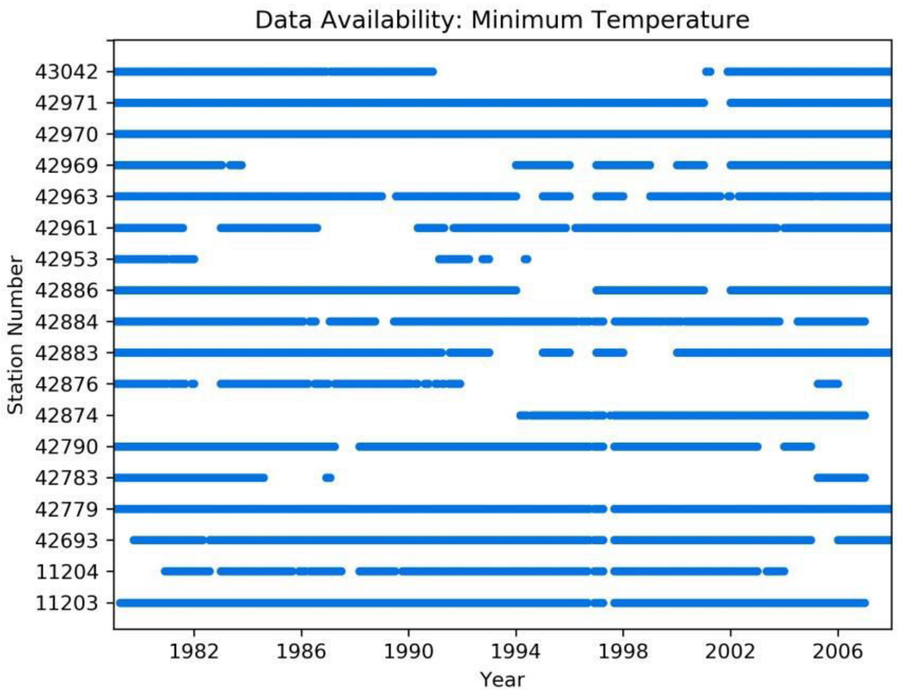
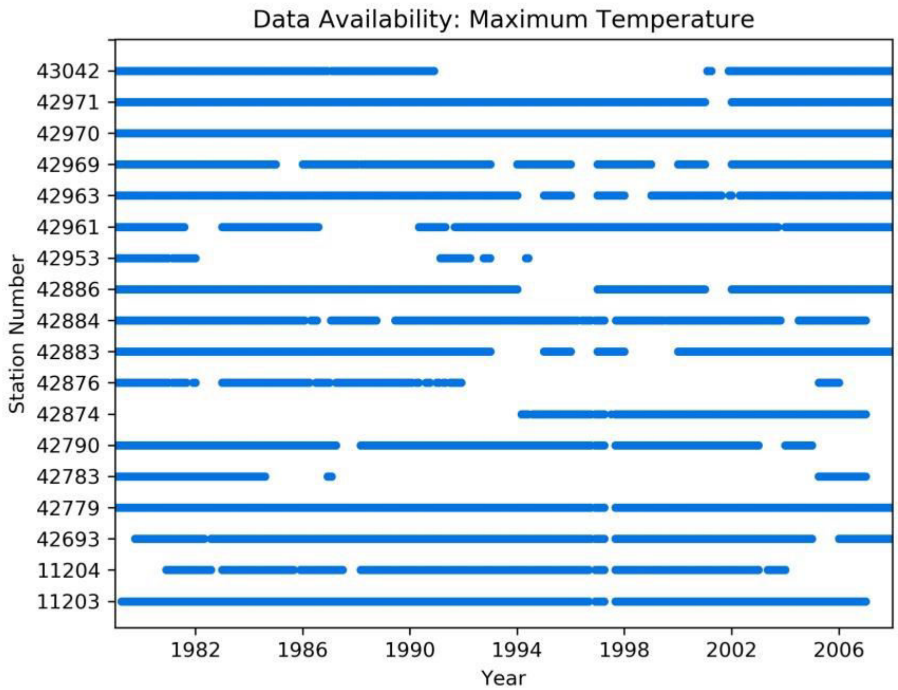
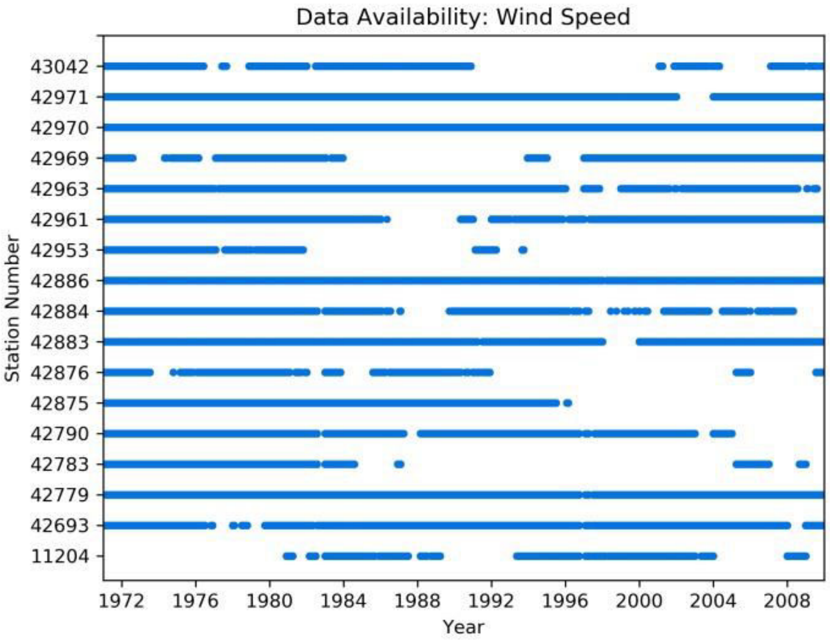
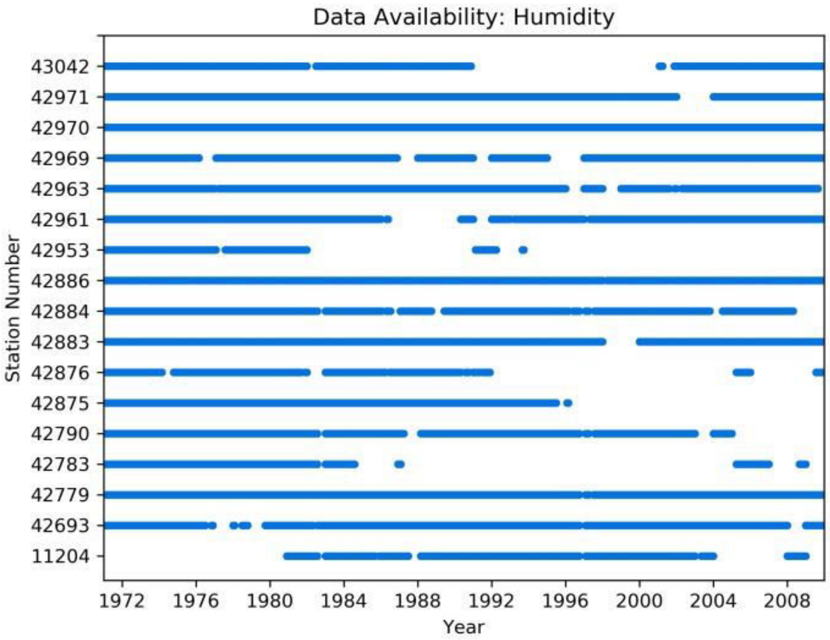
- Windspeed and relative humidity for 17 gauges (IMD)
- Sunshine hours for 5 gauges (IMD)





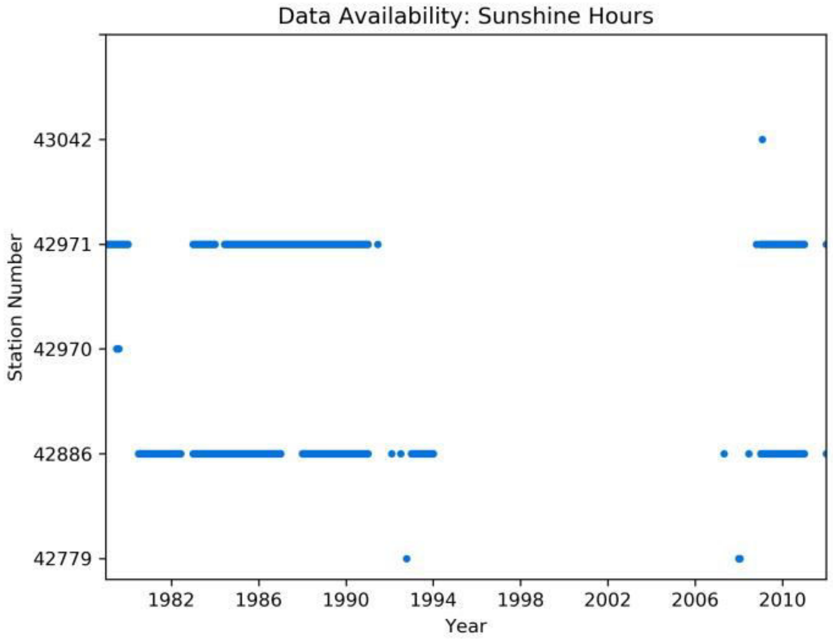
- Windspeed and relative humidity for 17 gauges (IMD)





Work Progress (Technical) : Baseline analysis of hydrometeorological data

- Sunshine hours for 5 gauges (IMD)



The analysis indicated large gaps (lots of missing values) in at-site data of hydrometeorological variables.

Priority was given to use gridded hydrometeorological data:

(i) 0.25˚ resolution rainfall from IMD

(ii) One-degree resolution temperature data from IMD

(iii) 0.3125˚ resolution wind speed, relative humidity, and solar radiation data from CFSR (Climate Forecast System Reanalysis) database

(iv) re-analysis data on wind speed, relative humidity, and solar radiation from different reanalysis data products (viz., NCEP, JRA, ERA and CRU)

Work Progress (Technical) : Details of collected gridded data

Data	Source	Quality	
		Period	Grid size (in degrees)
Precipitation	IMD	1901 - 2011	0.25
Maximum Temperature	IMD	1958 - 2013	1
Minimum Temperature	IMD	1958 - 2013	1
Wind Speed	NCEP	1951 - 2018	1 .88
	JRA	1958 - 2013	1 .25
Relative humidity	NCEP	1951 - 2018	1 .88
	JRA	1958 - 2013	1.25
Net Solar radiation	NCEP	1951 - 2018	1.88

PET estimated from NCEP and JRA data by FAO PM method

Work Progress on Milestones/activities

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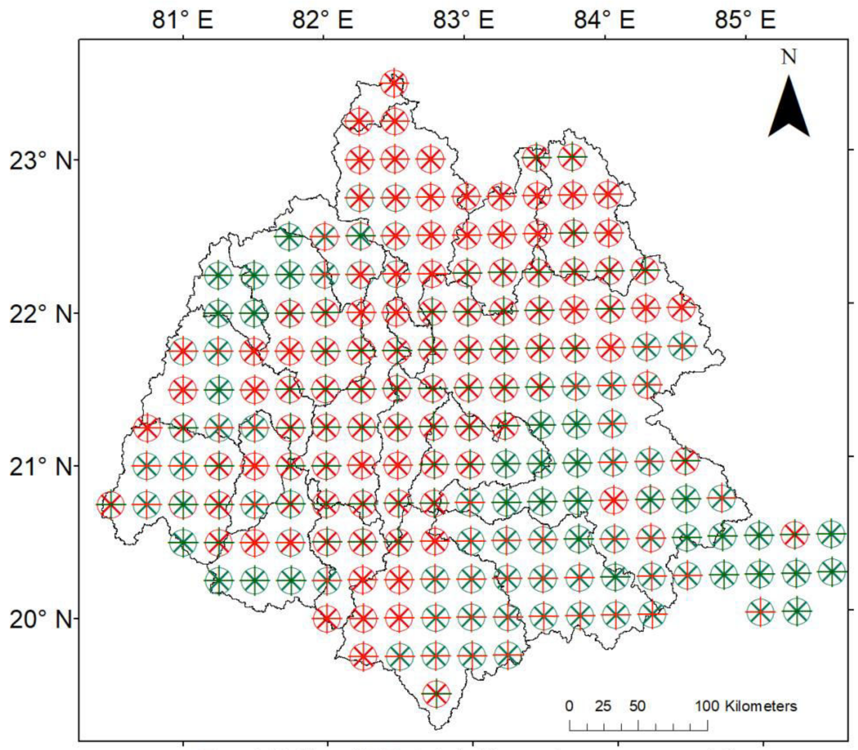
8	Modelling hydrological processes in Mahanadi basin for baseline (historical) period												
9	Modelling sediment transport in Mahanadi basin for baseline period												

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

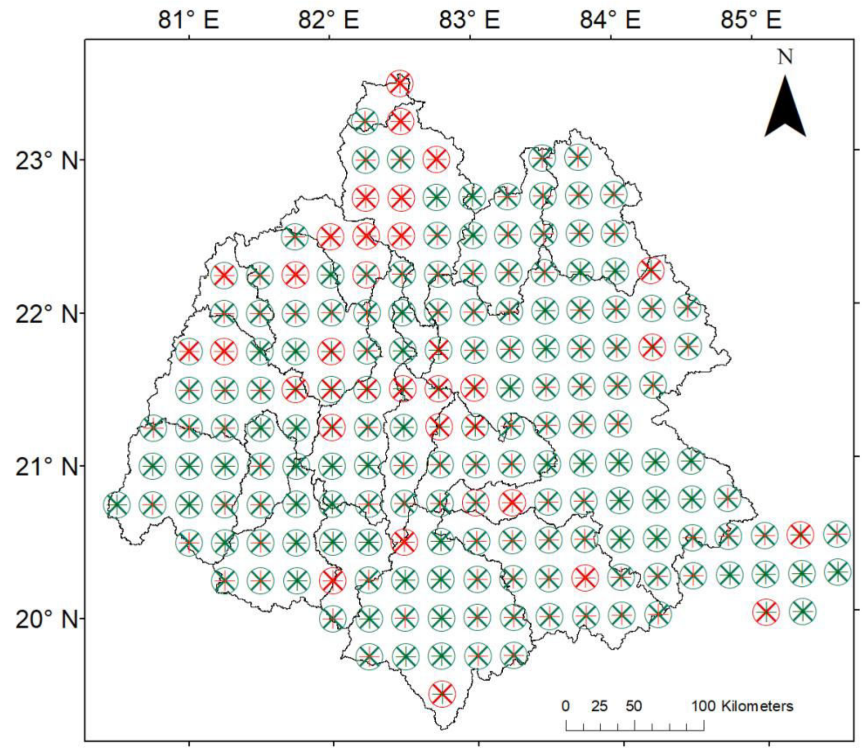
Work Progress (Technical) : Trend Analysis

- Evapotranspiration estimates were obtained using FAO penman Monteith method
- Stationarity of the hydrometeorological variables was examined using:
  (i)Mann-Kendall test
  (ii)t-test
  (iii)Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test
- Change point in the time series was identified using Pettit test
- Significance level considered: 5%

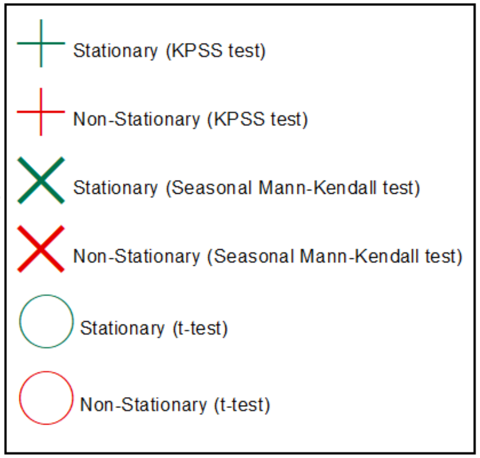
Work Progress (Technical) : Trend Analysis for precipitation



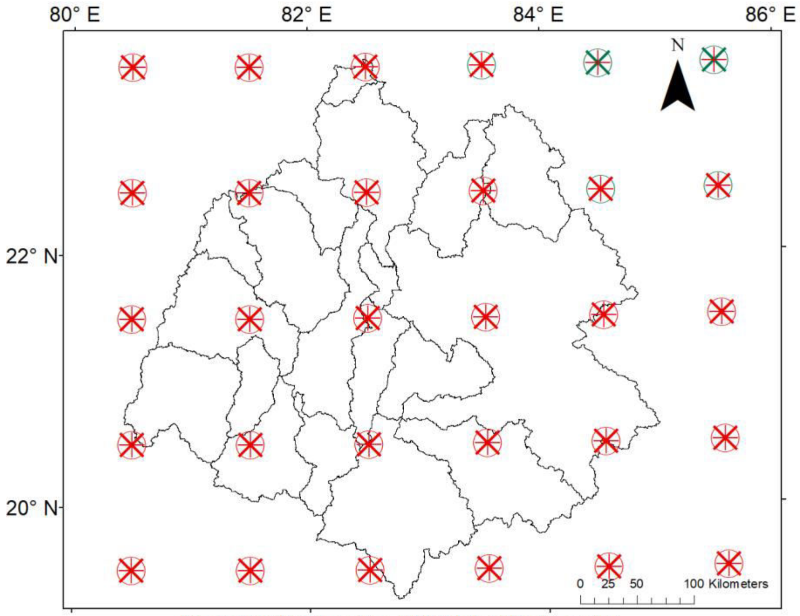
Annual precipitation (IMD data)



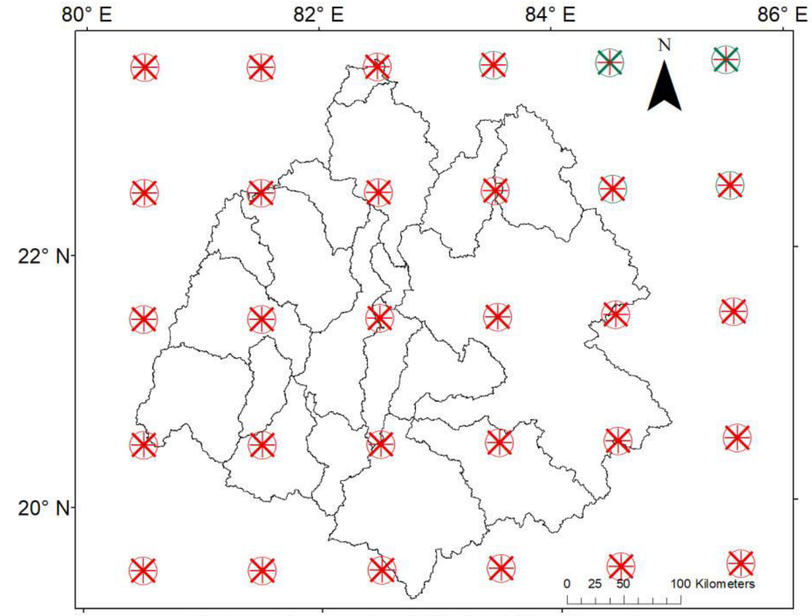
Annual maximum precipitation (IMD data)



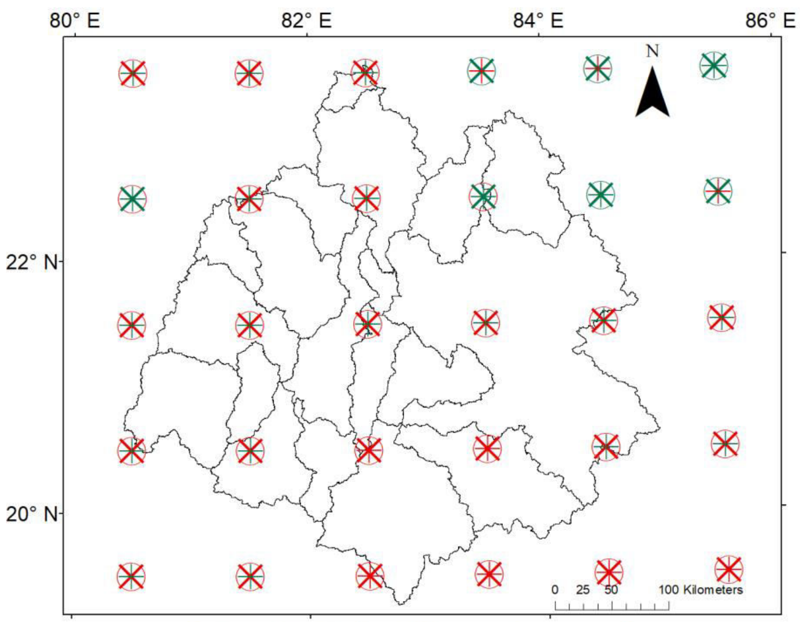
Work Progress (Technical) : Trend Analysis for Maximum temperature



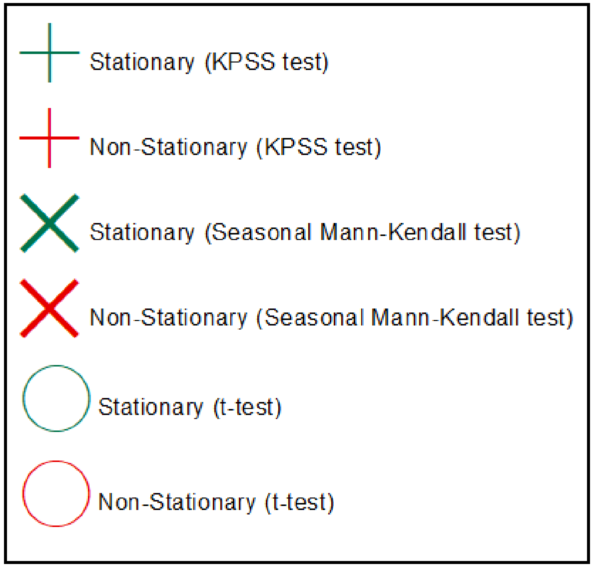
Maximum Temperature (IMD data) (Daily scale)



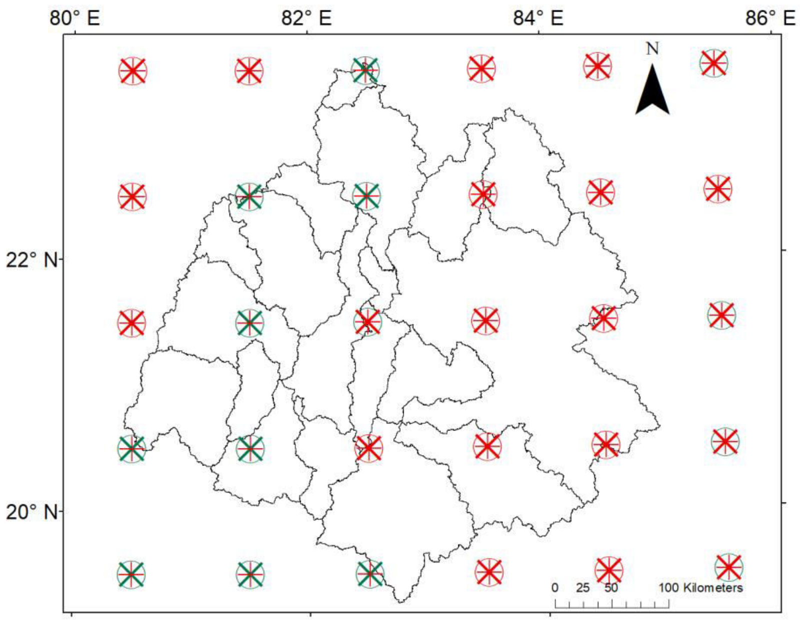
Maximum Temperature (IMD data) (Monthly scale)



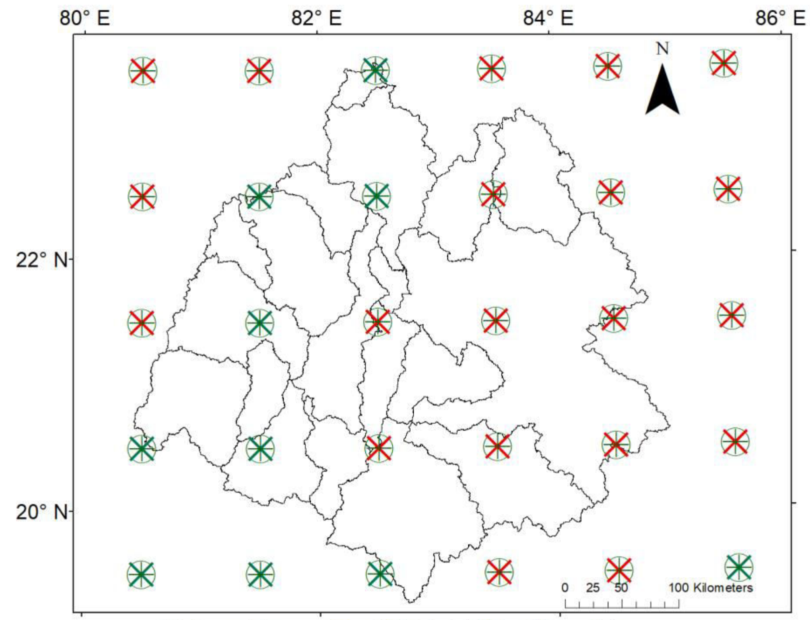
Maximum Temperature (IMD data) (Annual scale)



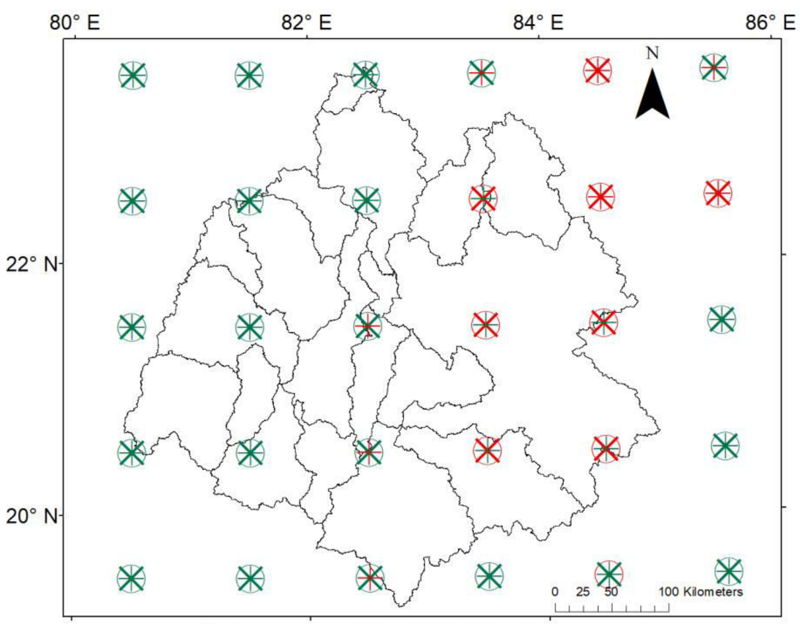
Work Progress (Technical) : Trend Analysis for Minimum temperature



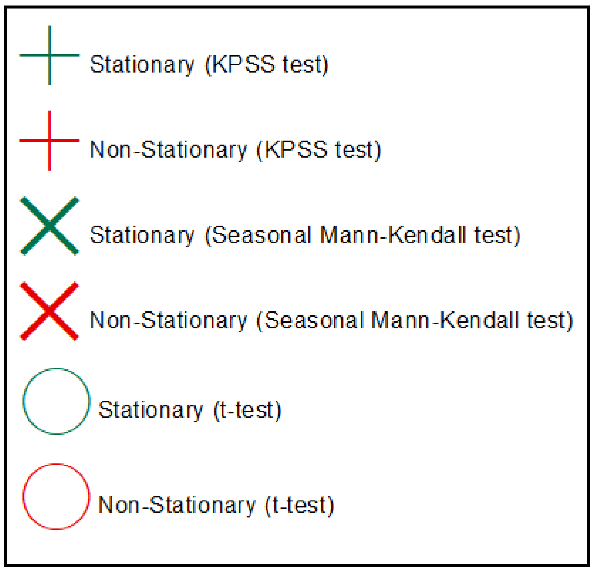
Minimum Temperature (IMD data) (Daily scale)



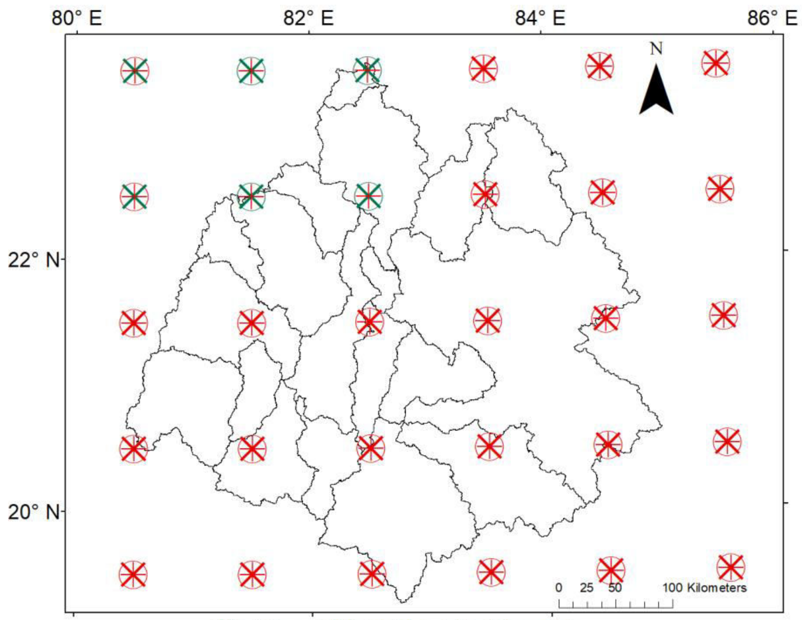
Minimum Temperature (IMD data) (Monthly scale)



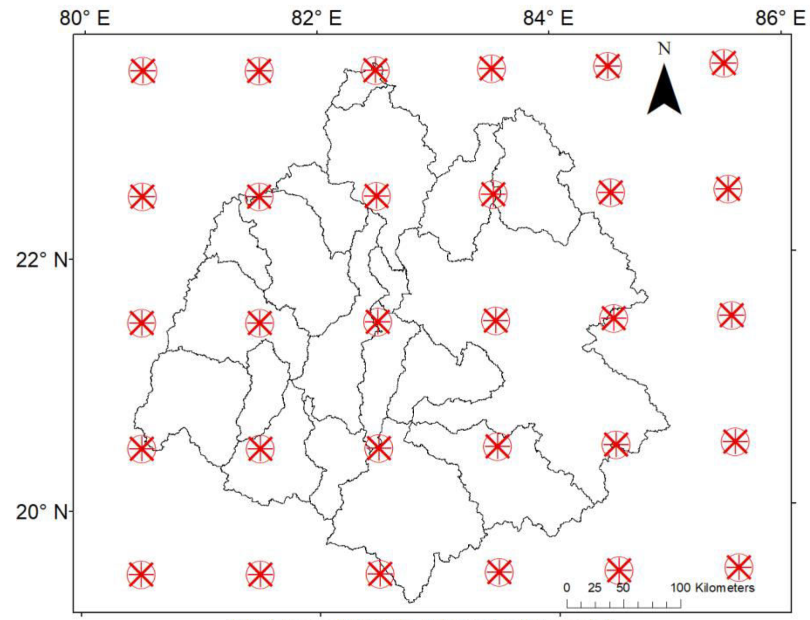
Minimum Temperature (IMD data) (Annual scale)



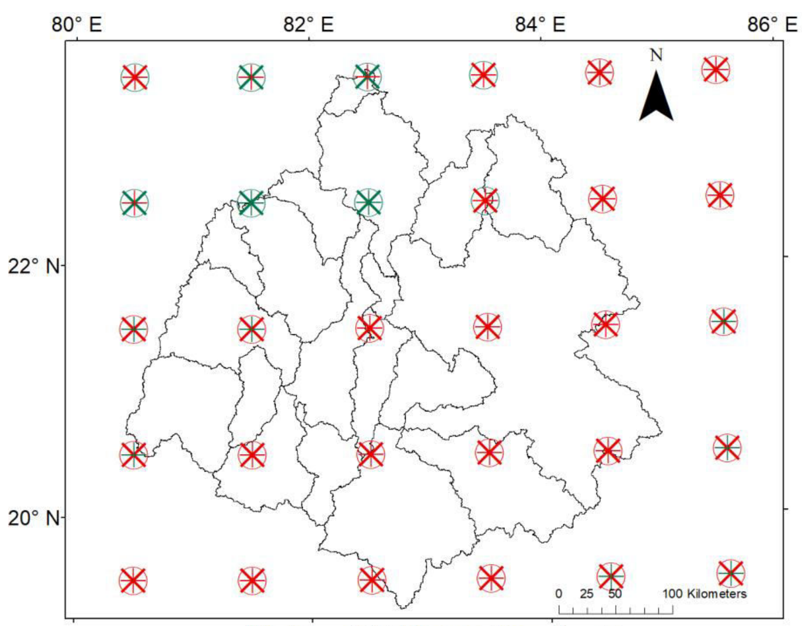
Work Progress (Technical) : Trend Analysis for Wind speed



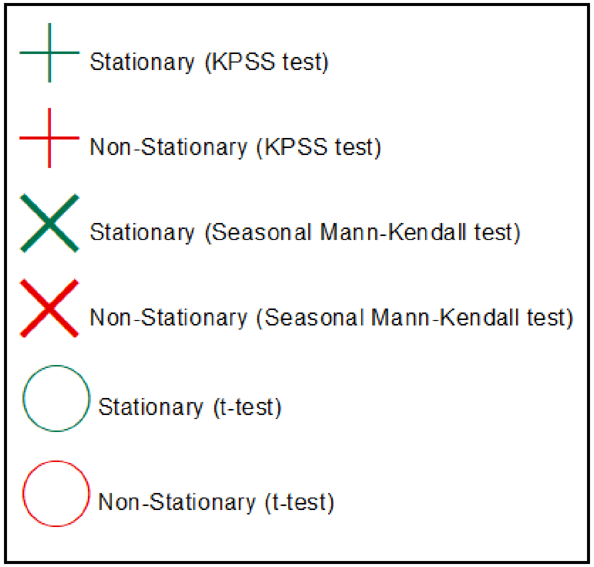
Wind Speed (NCEP data) (Dailyl scale)



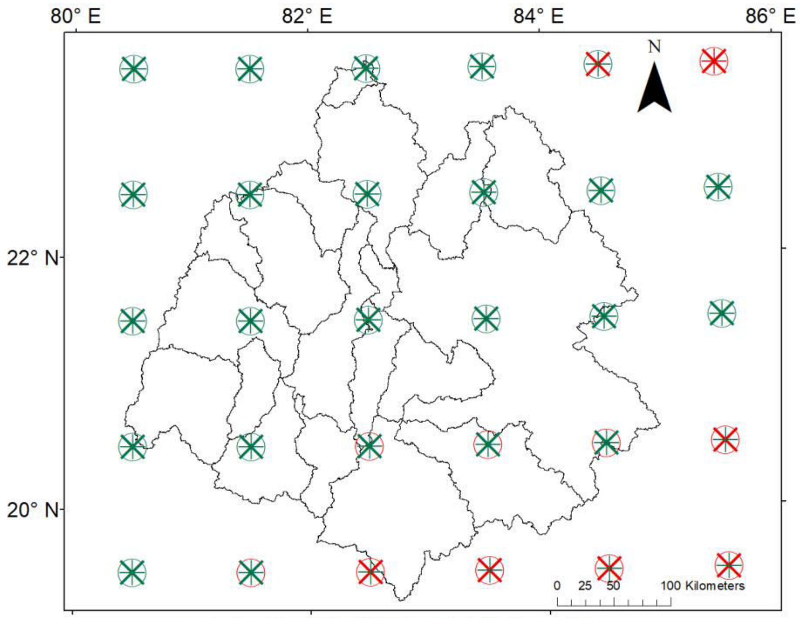
Wind Speed (NCEP data) (Monthly scale)



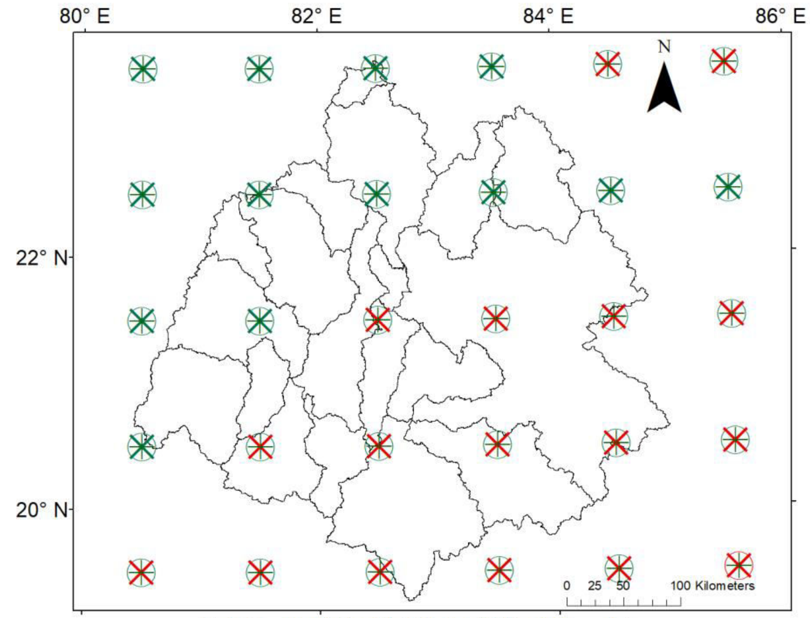
Wind Speed (NCEP data) (Annual scale)



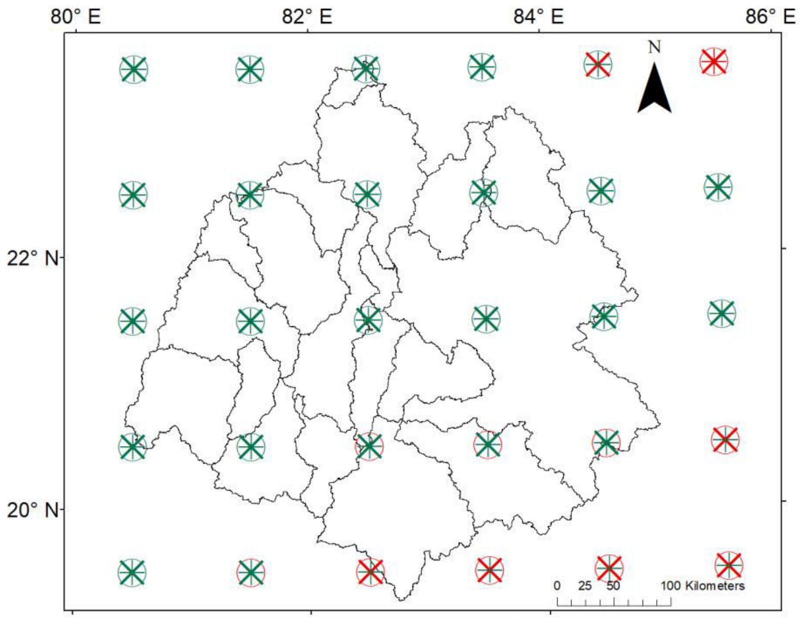
Work Progress (Technical) : Trend Analysis for Relative Humidity



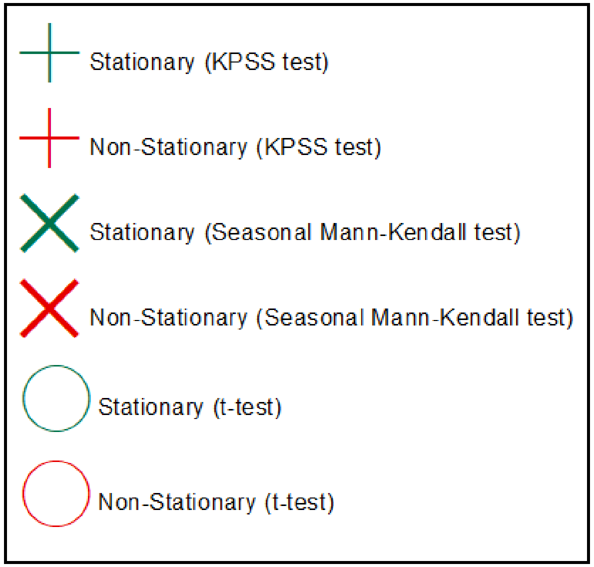
Relative Humidity (NCEP data) (Daily scale)



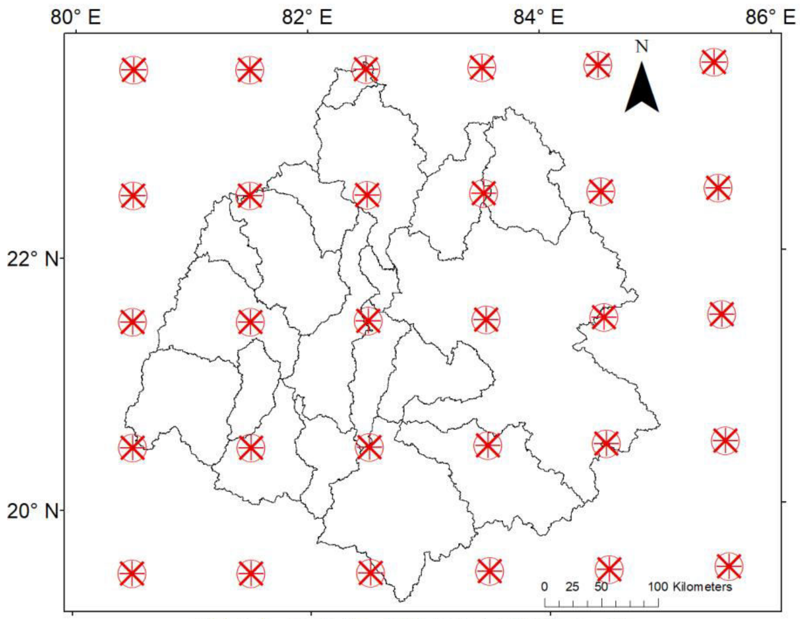
Relative Humidity (NCEP data) (Monthly scale)



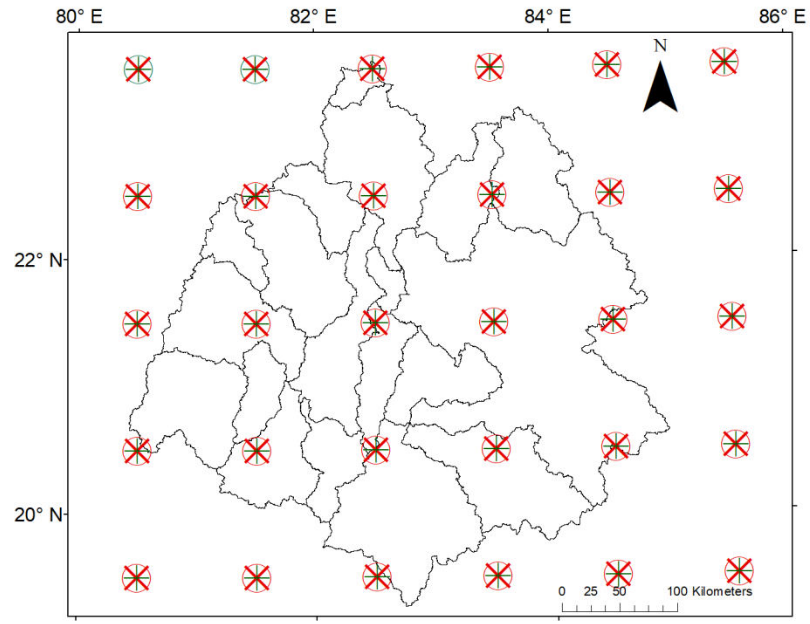
Relative Humidity (NCEP data) (Annual scale)



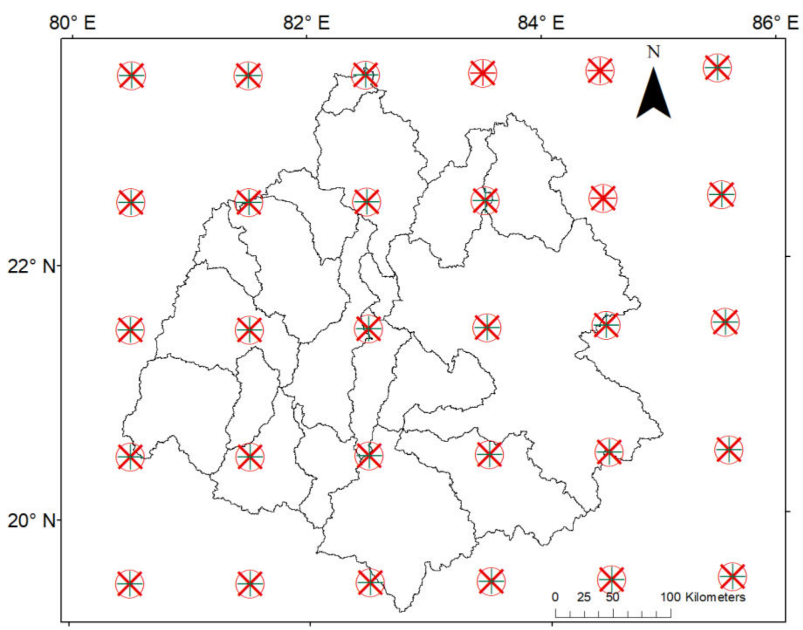
Work Progress (Technical) : Trend Analysis for Solar Radiation



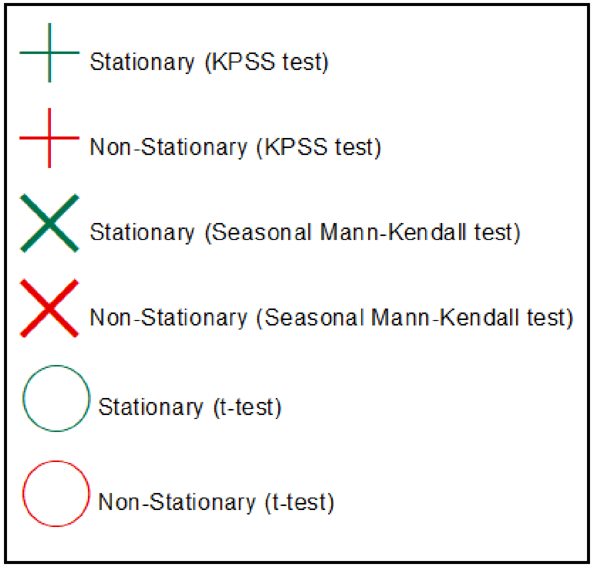
Net Solar Radiation (NCEP Data) (Daily Scale)



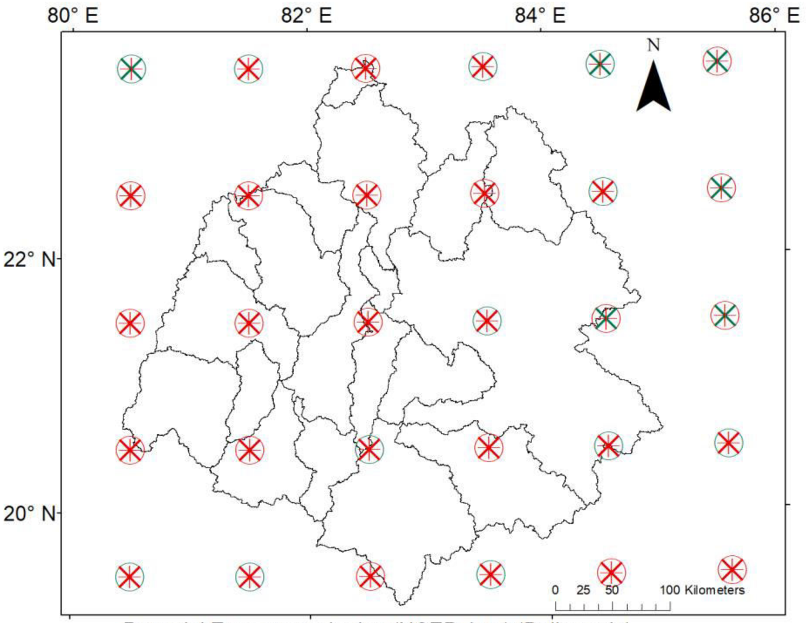
Net Solar Radiation (NCEP data) (Monthly scale)



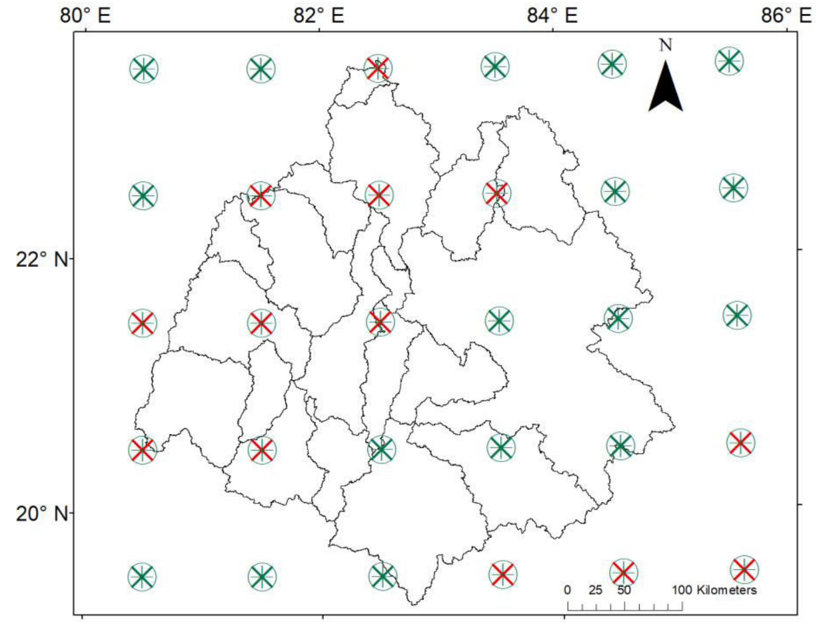
Net Solar Radiation (NCEP data) (Annual Scale)



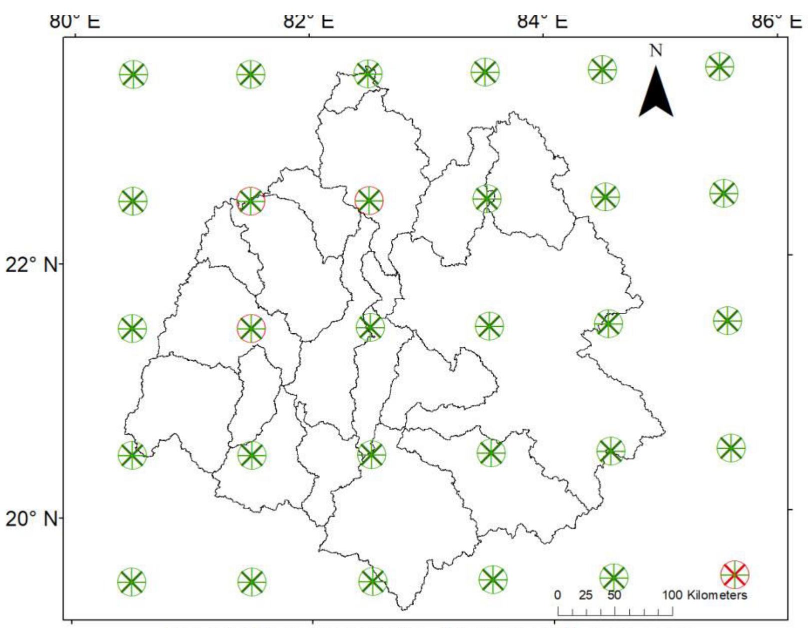
Work Progress (Technical) : Trend Analysis for PET



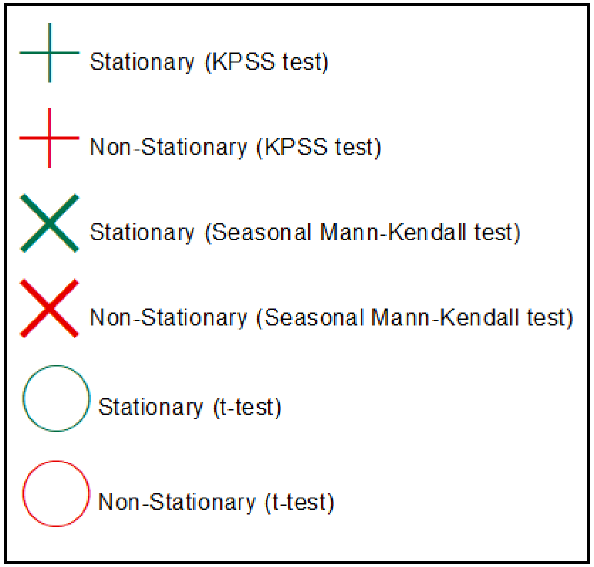
Potential Evapotranspiration (NCEP data) (Daily scale)



Potential Evapotranspiration (NCEP data) (Monthly scale)



Potential Evapotranspiration (NCEP data) (Annual scale)



Work Progress (Technical) : Trend Analysis

Variable	Data source	Daily			Monthly			Annual		
		t-test	MK	KPSS	t-test	MK	KPSS	t-test	MK	KPSS
Wind speed	NCEP	NS (91.4)	NS (88.6)	NS (100)	NS (84.3)	NS (88.6)	NS (52.9)	NS (82.9)	NS (87.1)	NS (71.4)
	JRA	NS (90.0)	NS (90.0)	NS (100)	NS (78.6)	NS (88.6)	NS (92.9)	NS (78.6)	NS (80.0)	NS (98.6)
RH	NCEP	NS (67.1)	NS (74.3)	NS (100)	S (87.1)	NS (67.1)	S (100)	S (58.6)	S (62.9)	S (84.3)
	JRA	NS (100)	NS (100)	NS (100)	NS (95.7)	NS (100)	S (95.7)	NS (100)	NS (100)	S (72.9)
PET	NCEP	NS (64.1)	NS (73.4)	NS (100)	S (96.9)	S (54.7)	S (100)	S (76.6)	S (81.3)	S (87.5)
	JRA	NS (53.1)	S (51.6)	NS (100)	S (96.9)	NS (51.6)	S (100)	S (64.1)	S (68.8)	S (70.3)
Solar Radiation	NCEP	NS (98.6)	NS (98.6)	NS (95.7)	NS (74.3)	NS (98.6)	S (100)	NS (98.6)	NS (98.6)	S (91.4)
T-max	IMD	NS (75.0)	NS (84.4)	NS (100)	S (90.6)	NS (81.3)	S (100)	NS (60.9)	NS (60.9)	S (75.0)
T-min	IMD	NS (54.7)	NS (70.3)	NS (100)	S (100)	NS (65.6)	S (100)	S (70.3)	S (75.0)	S (57.8)

*() values indicated percentage of grids in Mahanadi basin

Verification of Stationarity in Annual Maximum Flows

Sl.No	Stream Gauge Location	Mann-Kendall Test		KPSS Test	
		Test Stastic	Critical Value at 5% Significance	Test Statistic	Critical Value at 5% Significance
1	Andhiyarkore	0.54	1.96	0.14	0.46
2	Bamnidihi	3.78	1.96	0.44	0.46
3	Baronda	1.11	1.96	0.38	0.46
4	Basantpur	1.48	1.96	0.23	0.46
5	Ghatora	1.99	1.96	0.19	0.46
6	Jondhra	1.64	1.96	0.41	0.46
7	Kantamal	0.71	1.96	0.21	0.46
8	Kesinga	0.73	1.96	0.29	0.46
9	Kotni	0.02	1.96	0.16	0.46
10	Kurubhata	1.05	1.96	0.22	0.46
11	Manendragarh	2.54	1.96	0.39	0.46
12	Pathardhi	0.73	1.96	0.29	0.46
13	Rajim	0.31	1.96	0.12	0.46
14	Rampur	0.06	1.96	0.22	0.46
15	Salebhata	0.00	1.96	0.13	0.46
16	Seorinarayan	0.91	1.96	0.32	0.46
17	Simga	0.66	1.96	0.18	0.46
18	Sundargarh	0.42	1.96	0.13	0.46
19	Tikarapara	0.86	1.96	0.26	0.46

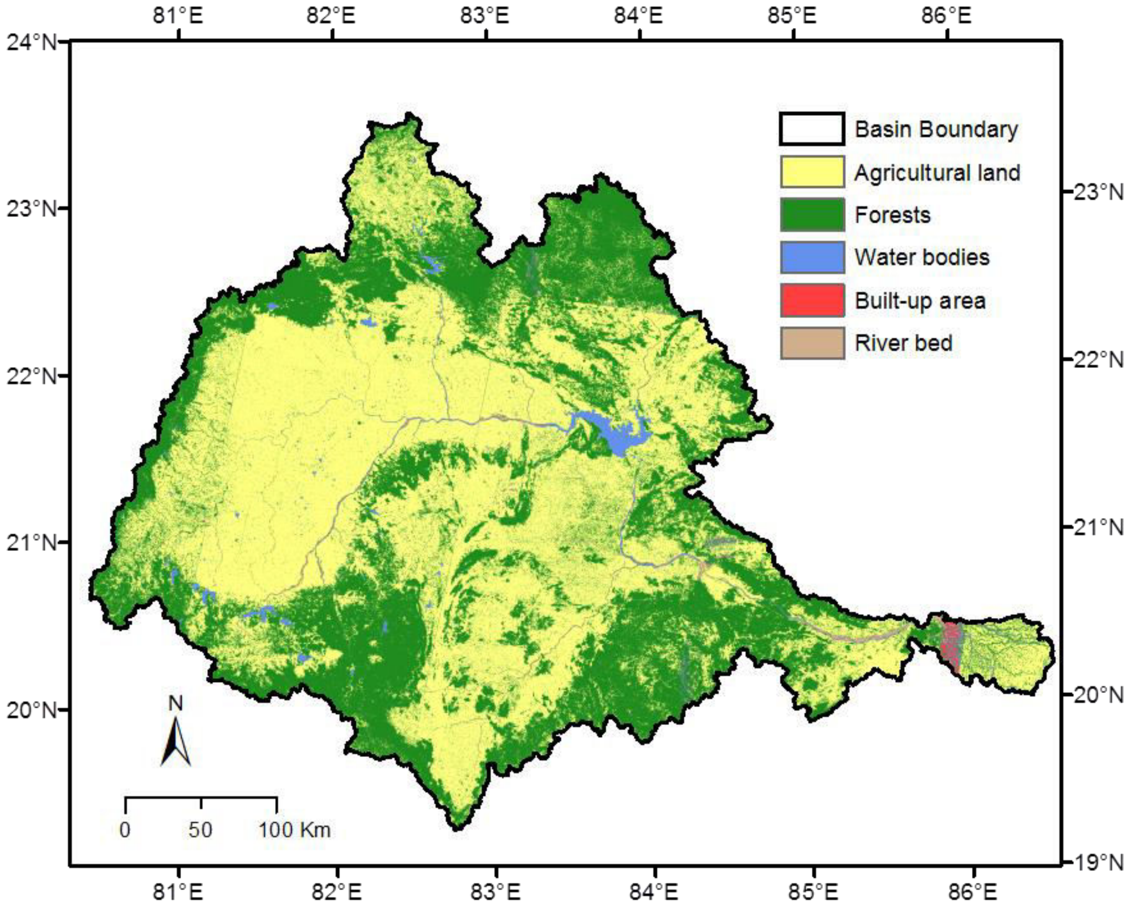
Work Progress (Technical) : Trend analysis

Results

- The hydrometeorological variables could be considered nonstationary for majority of the grids at daily scale
- The tests yielded contrasting results for most of the variables at monthly and annual scales
- They were consistent in indicating non-stationary in wind speed and stationarity in minimum temperature and evapotranspiration for majority of the grids at annual scale
- The tests also indicated non-stationarity in daily and annual rainfall, daily flows, but stationarity in annual maximum rainfall and peak flows

Work Progress (Technical) : Data collected for rainfall-runoff modelling

Landuse landcover (LULC)



LULC map for 1989-90 (based on Landsat TM imageries)

LULC classes	1985	1989 -1990	2003	2004 -2005	2005 -2006	2006 -2007	2007 -2008	2008 -2009	2009 -2010	2010 -2011
Built up land (%)	0.22	0.31	0.31	0.43	0.36	0.36	0.28	0.33	0.33	0.33
Agriculture (%)	56.41	60.76	59.63	60.43	58.55	59.24	60.06	59.43	60.02	59.98
Forest (%)	37.56	36.80	33.48	31.03	31.38	31.39	31.46	31.36	31.34	31.36
Water Bodies (%)	1.19	1.51	1.62	2.22	2.77	2.11	2.19	2.51	2.06	1.92

1985: (AVHRR images -1 km resolution)-Dadhwal et al., 2010

1989-90: (Landsat images – 30m resolution)- Present study

2003: (AWiFs -56 m resolution) -Dadhwal et al., 2010

2004-2011: Information extracted in present study from NRSC processed data

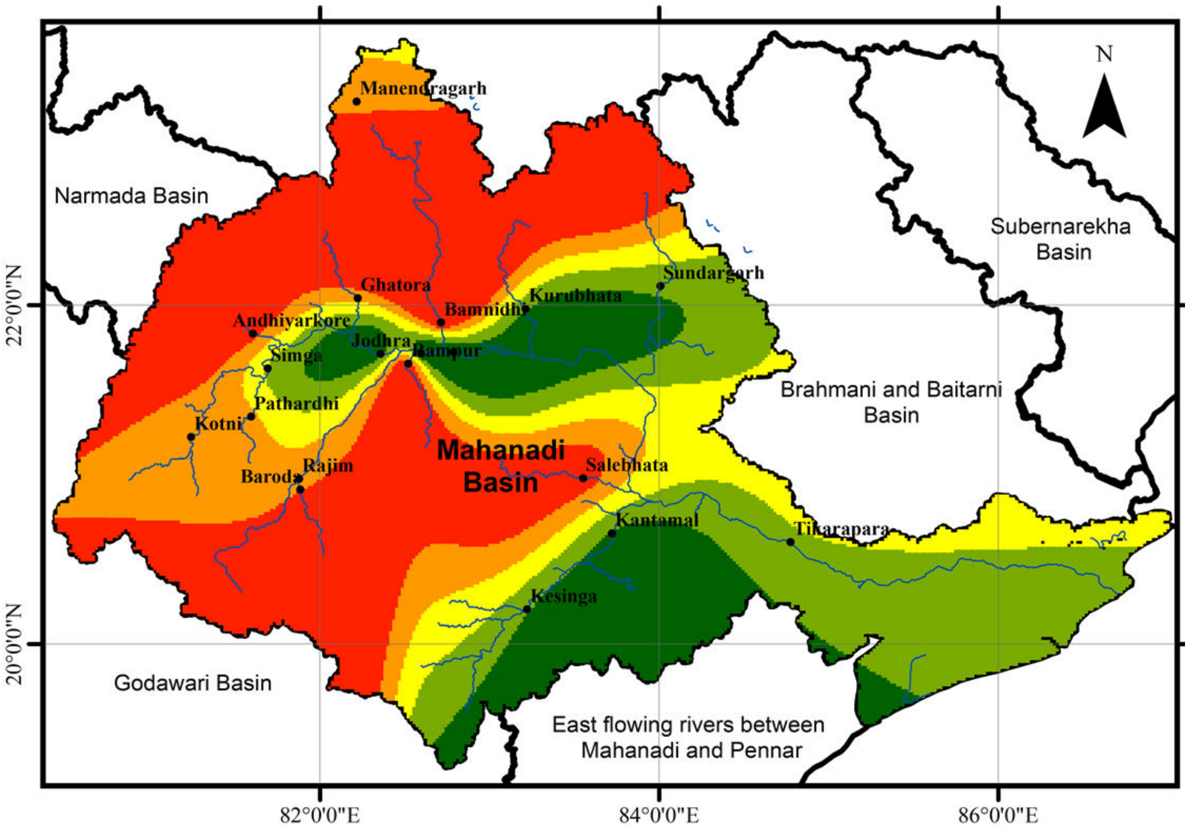
Conclusions drawn based on LULC analysis

- Forest cover has declined by 6.2% of the total area of the basin
- Area of Agricultural land has increased by 3.6%
- Area of surface water bodies has increased by (0.73%)
- Built up land increased by 0.21% during 1985-2005, and thereafter decreased

Extraction of LULC information for Mahanadi basin from preprocessed LULC data procured from NRSC

Sl. No	Class Name	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11
		Area(Km^2)	Area(Km^2)	Area(Km^2)	Area(Km^2)	Area(Km^2)	Area(Km^2)	Area(Km^2)
1	Build up	576.82	489.89	489.33	373.86	447.30	445.30	446.69
2	Kharif only	45149.15	47242.46	42053.38	32990.10	38215.09	34032.65	33604.76
3	Rabi only	3259.72	1362.65	3063.07	2547.41	1784.94	3178.14	3939.70
4	Zaid only	3.57	5.13	117.42	254.01	796.01	544.85	403.68
5	Double / tripple	10211.45	18440.23	17934.94	23260.24	18431.55	28896.55	24805.94
6	Current fallow	23078.77	11954.25	16772.31	22008.08	20978.31	14356.02	18195.29
7	Plantation/orchard	249.29	393.34	391.38	392.71	392.10	389.89	390.27
8	Evergreen forest	82.97	82.72	82.77	83.15	83.26	83.58	83.24
9	Deciduous forest	34306.00	33896.35	33900.58	35035.01	34522.58	34498.63	34530.65
10	Scrub/Deg. forest	7692.58	8578.35	8576.83	7538.63	7925.21	7915.77	7911.99
11	Littoral swamp	3.95	4.00	3.94	3.92	4.07	3.51	3.63
12	Grassland	520.69	191.06	189.53	190.10	189.47	188.35	189.10
13	Other wasteland	2234.61	3055.99	3016.30	2600.97	2990.73	2849.64	3055.86
14	Gullied	365.16	355.07	356.10	354.96	355.57	354.77	355.31
15	Scrubland	4826.69	5764.08	5762.52	4973.70	5053.29	5049.87	5054.39
16	Water bodies	3011.14	3758.99	2864.37	2967.99	3405.45	2787.57	2604.32
17	Shifting Cultivation	43.36	41.37	41.17	41.11	40.98	40.82	41.10

Work Progress (Technical): Identification of stream gauge deficient zones



Type of zone	Range for MI index	% area
Highly deficit zone	$0 \le$ MI index < 0.2	37.1
Deficit zone	$0.2 \le$ MI index < 0.4	14.4
Average zone	$0.4 \le$ MI index < 0.6	12.4
Above average zone	$0.6 \le$ MI index < 0.8	21.9
Excess zone	$0.8 \le$ MI index ≤ 1	14.2

Sl. No	Station Name	Rank
1	Andhiyarkore	10
2	Bamnidhi	2
3	Baroda	15
4	Basantpur	11
5	Ghatora	8
6	Jodhra	1
7	Kantamal	14
8	Kesinga	9
9	Kotni	7
10	Kurubhata	5
11	Manendragarh	13
12	Pathardhi	18
13	Rajim	12
14	Rampur	19
15	Salebhata	17
16	Seorinarayan	4
17	Simga	6
18	Sundargarh	16
19	Tikarapara	3

Work Progress on Milestones/activities

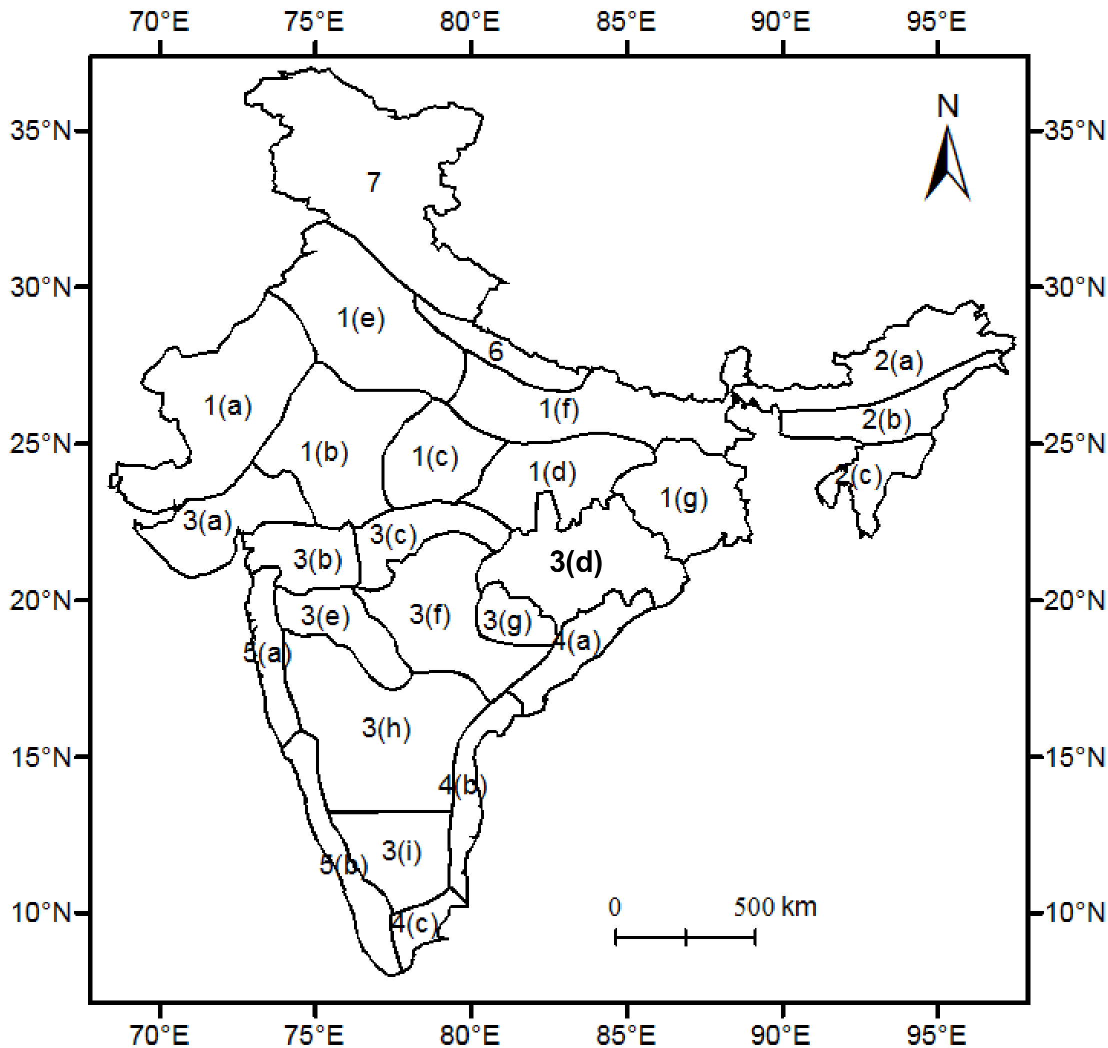
Project start date: 07.03.2018

Sl. No	Milestone/ Activity	0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
6	Trend analysis of observed meteorological, hydrological and sediment data												
7	Analysis on hydrometeorological Extremes based on the base line data												
8	Modelling hydrological processes in Mahanadi basin for baseline (historical) period												
9	Modelling sediment transport in Mahanadi basin for baseline period												

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

Work Progress (Technical): Analysis on hydrometeorological Extremes (Floods)

Hydrometeorological zones and sub-zones in India [Ref: CWC, 1983]



Zones: 7

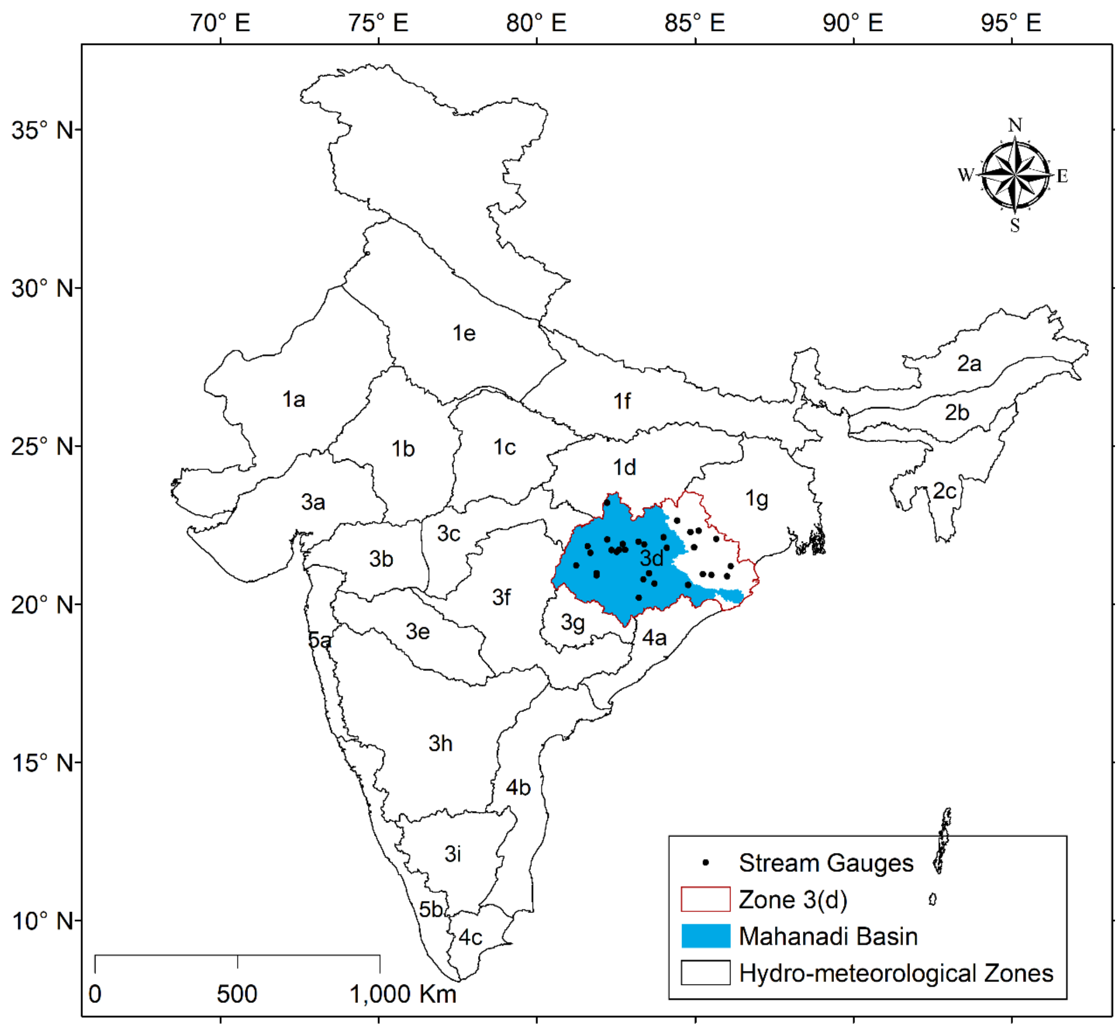
Sub-zones: 26

Khosla Committee

CWC. 1983. Flood estimation report. Directorate of Hydrology (Small Catchments), CWC, New Delhi.

Work Progress (Technical): Analysis on hydrometeorological Extremes (Floods)

Investigating homogeneity of catchments in zone 3(d) for flood estimation in L-moment framework



H1	7.8
H2	7.4
H3	6.2
Region size (station years)	934
No. of catchments	31

Acceptably homogeneous : H < 1

Possibly heterogeneous : 1≤ H < 2

Definitely heterogeneous : H ≥ 2

Work Progress on Milestones/activities

Project start date: 07.03.2018

Sl. No	Milestone/ Activity	Time in Months											
		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
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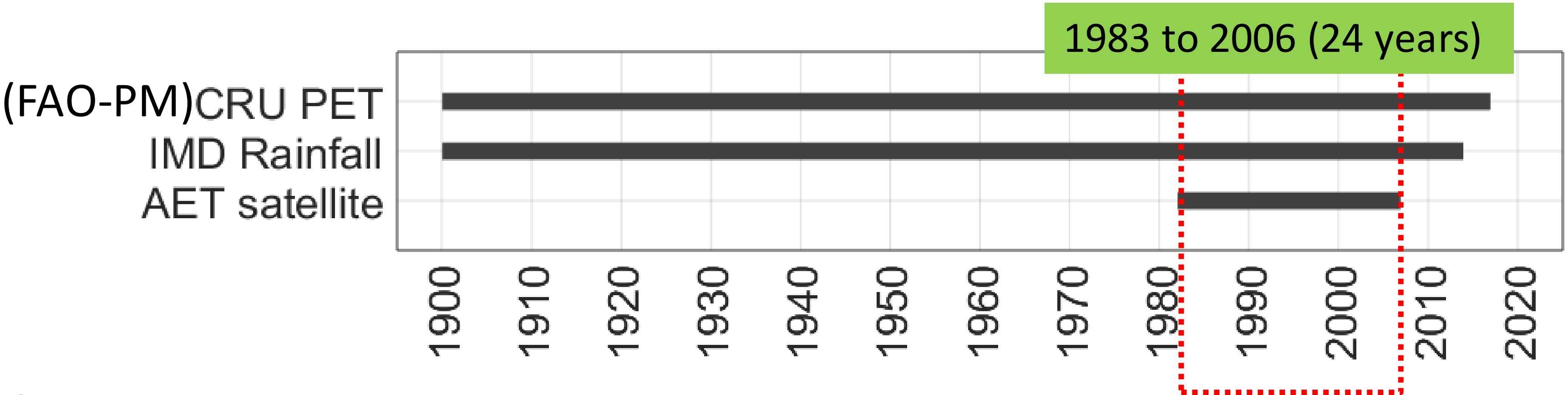
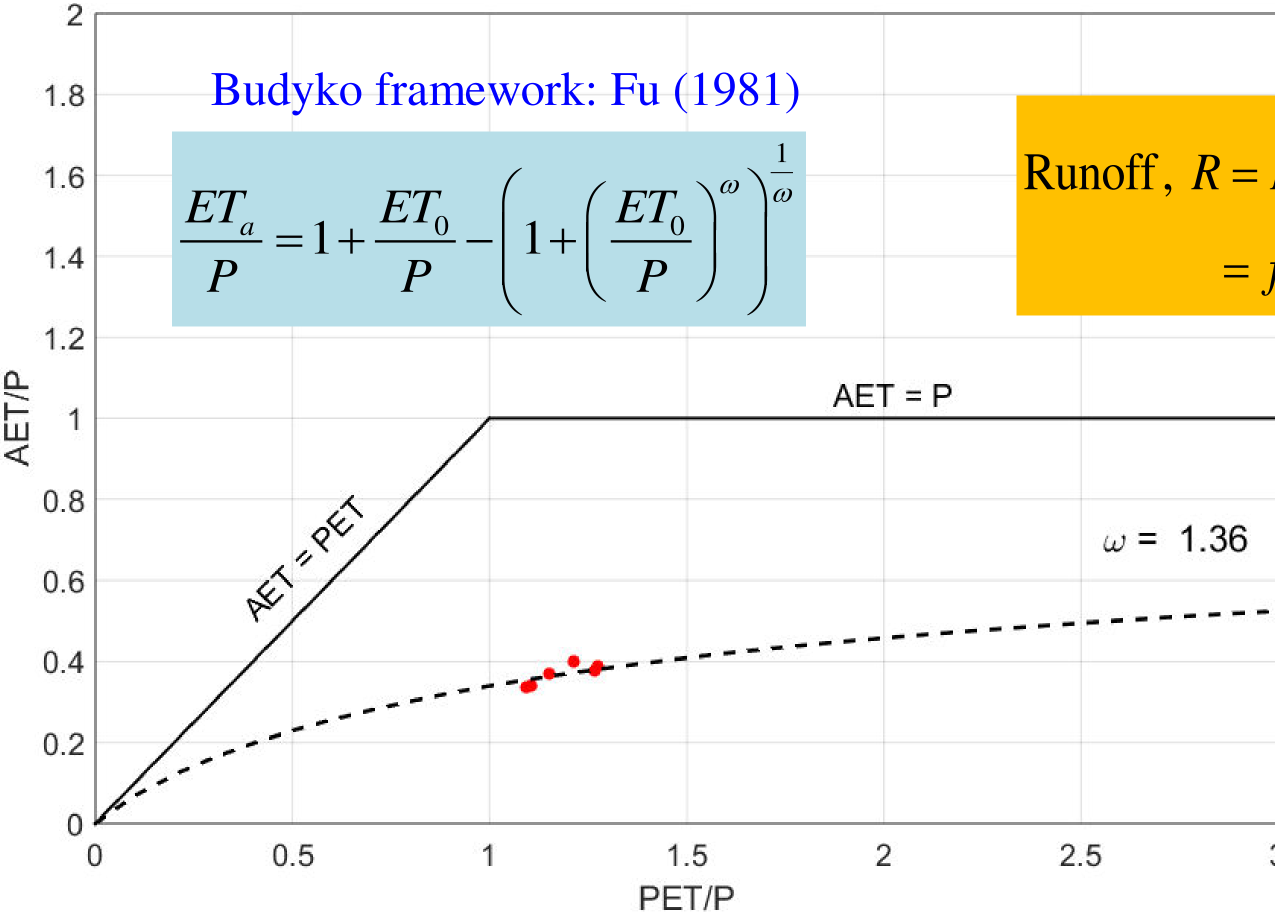
Work Progress (Technical): Annual runoff re-construction from climate data



Budyko framework: Fu (1981)

$$\frac{ET_a}{P} = 1 + \frac{ET_0}{P} - \left(1 + \left(\frac{ET_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}}$$

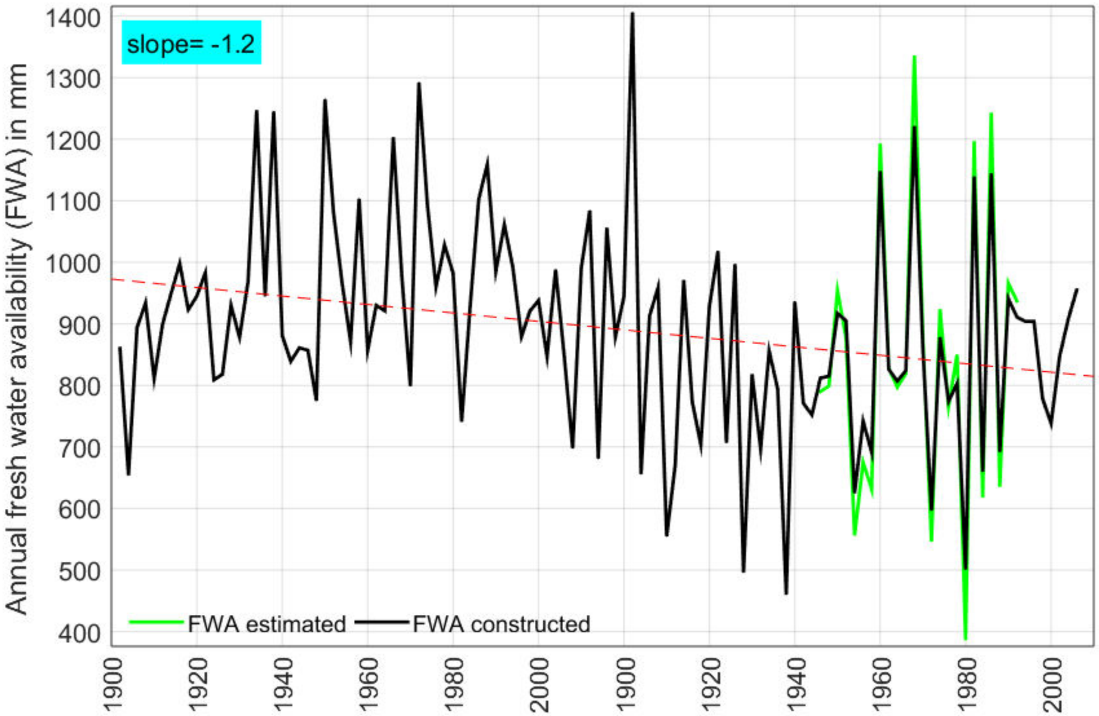


$$\text{Runoff},\ R = P - ET_a = \left(P^{\omega} + ET_0^{\ \omega}\right)^{\frac{1}{\omega}} - ET_0$$
$$= f\left(ET_0, P, \omega\right)$$

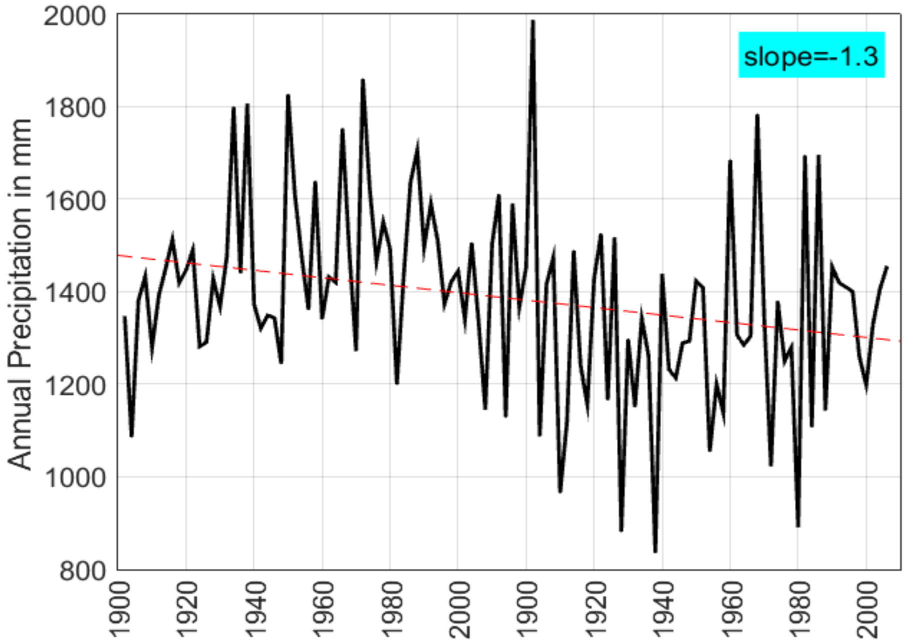
Work Progress (Technical): Annual runoff re-construction from climate data

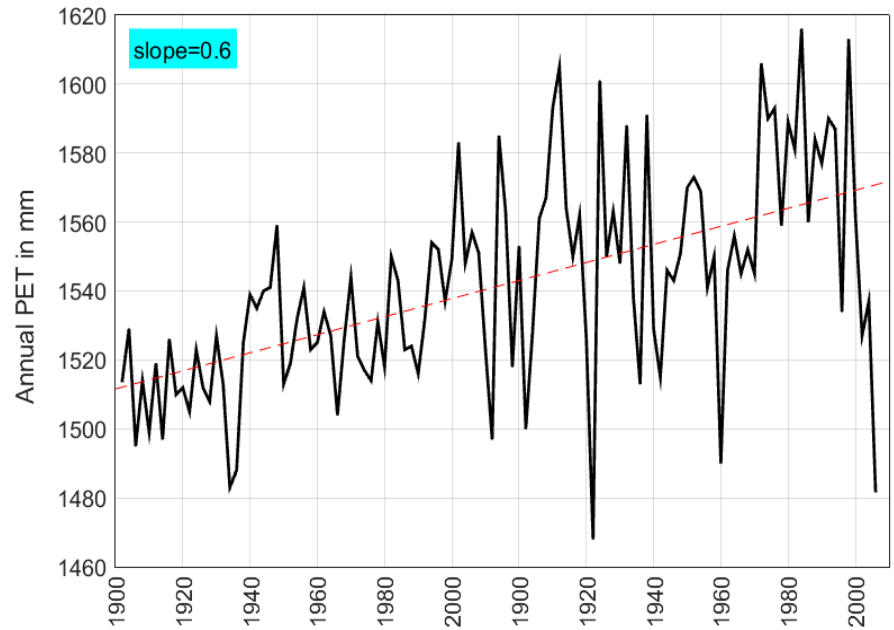
Constructed $FWA = \left(P^{\omega} + ET_0^{\ \omega}\right)^{\frac{1}{\omega}} - ET_0$

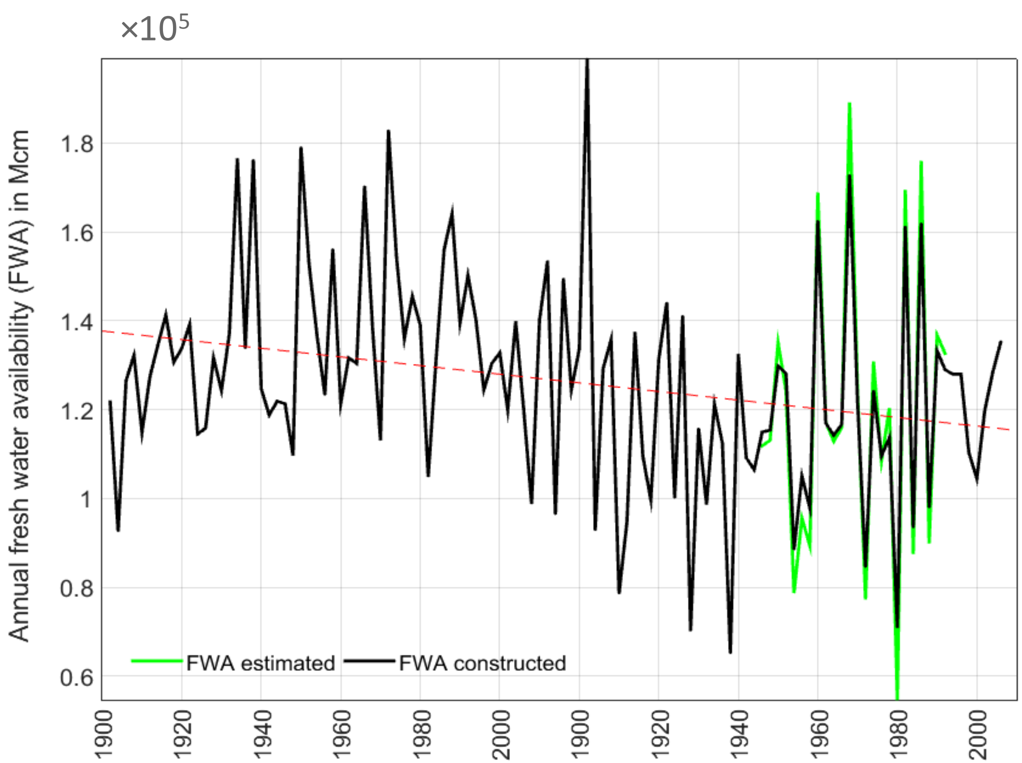
Estimated $FWA = P - ET_a$



- Re-constructed annual runoff series has statistically significant decreasing trend at 99% confidence level during 1901-2013 period
- 12.3% decrease in annual precipitation and 3.9% increase in annual PET (FAO-PM) has caused **decrease in annual fresh water availability** (i.e., Precipitation- AET) **by 16 %** in Mahanadi basin during this period







- Reduction in runoff by **21993 Mm^3**

Work Progress on Milestones/activities

Project start date: 07.03.2018

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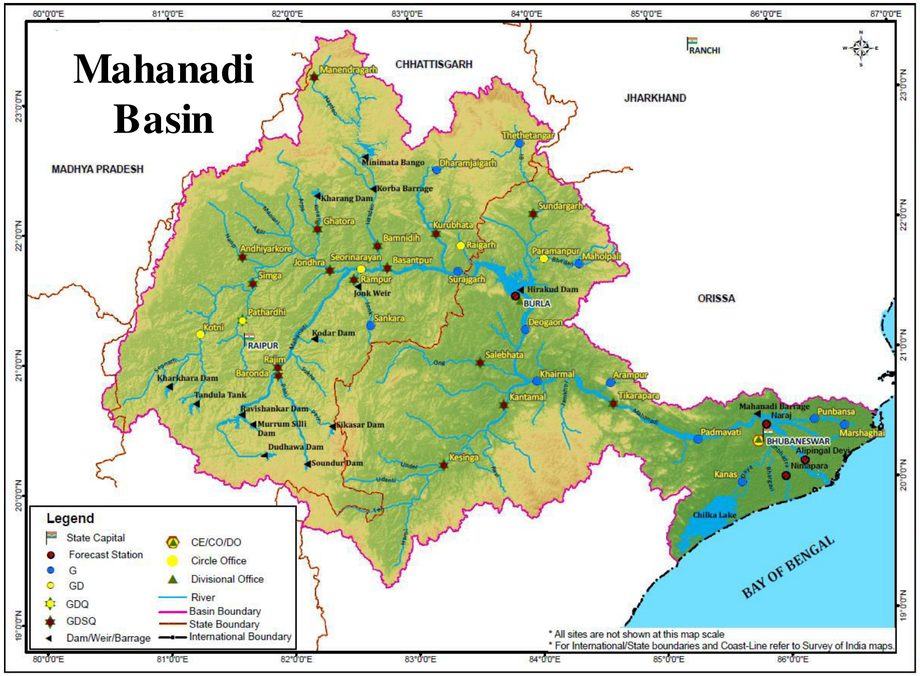

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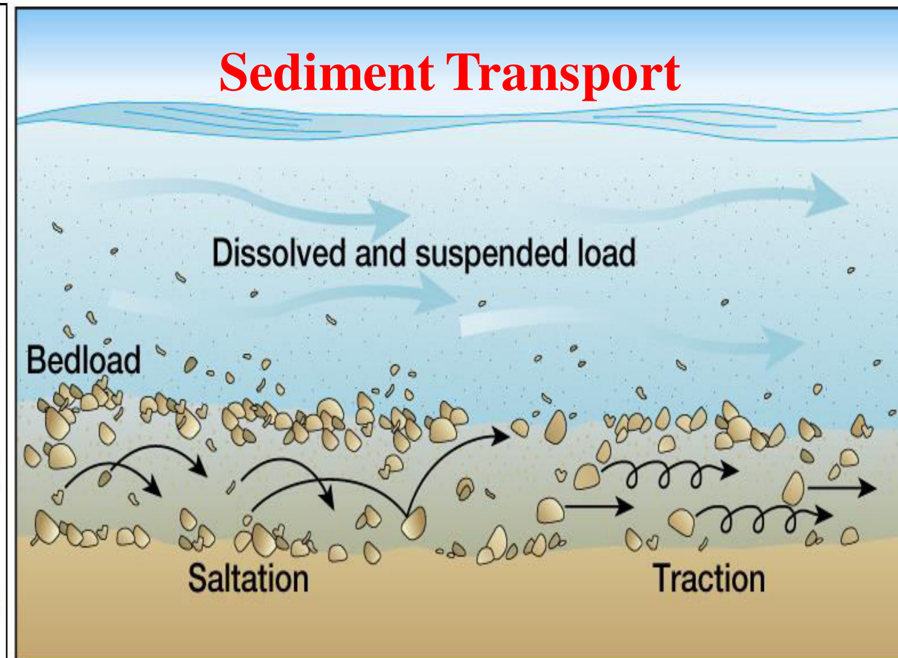
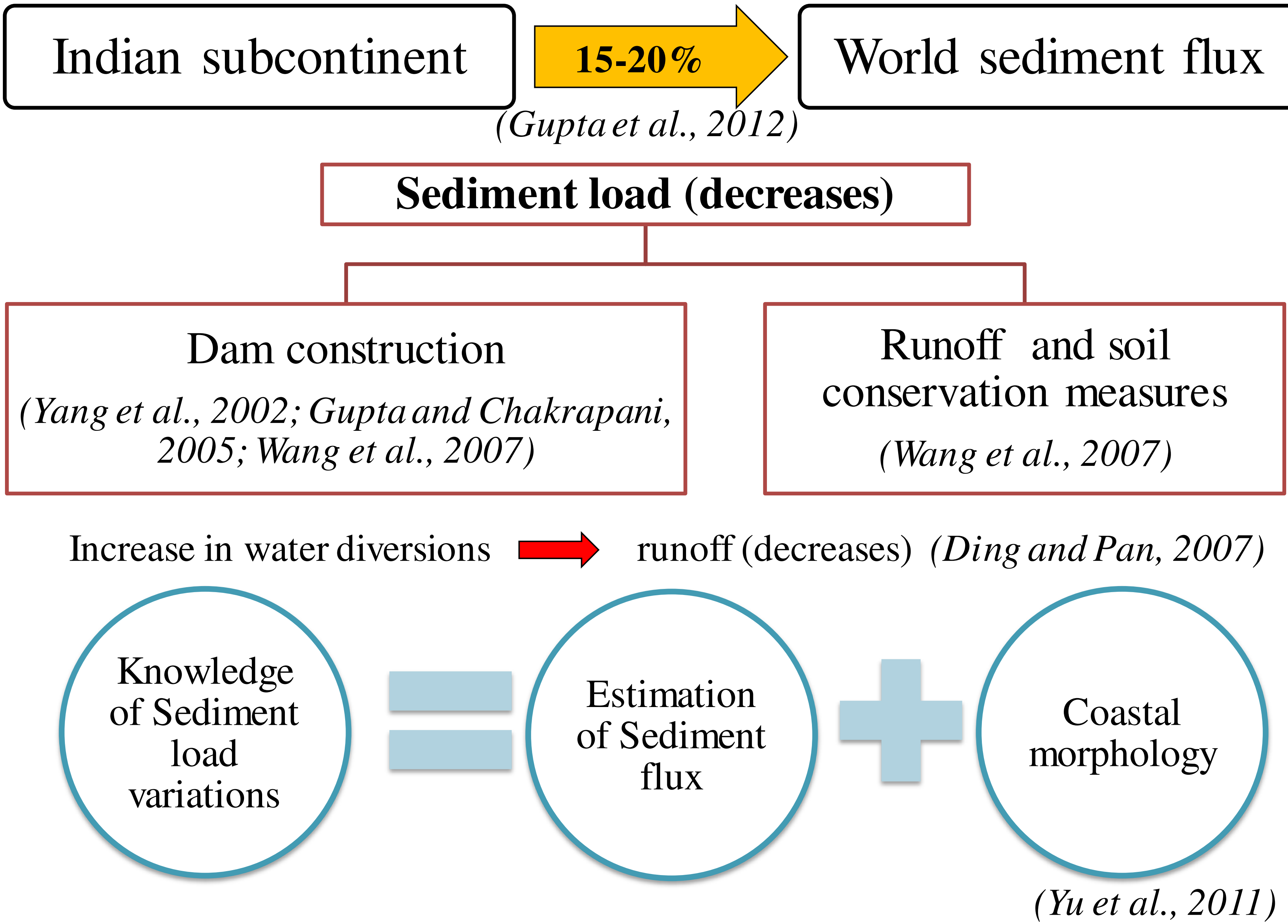


https://goo.gl/images/Pt3F9s

Terrestrial ecosystem → ***RIVERS*** ← **Coastal ecosystem**

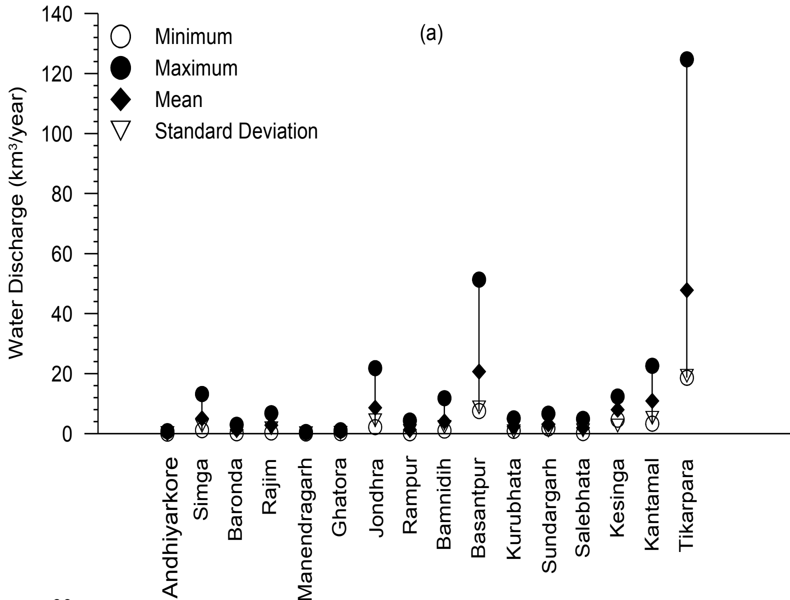
Past research



Summary of findings

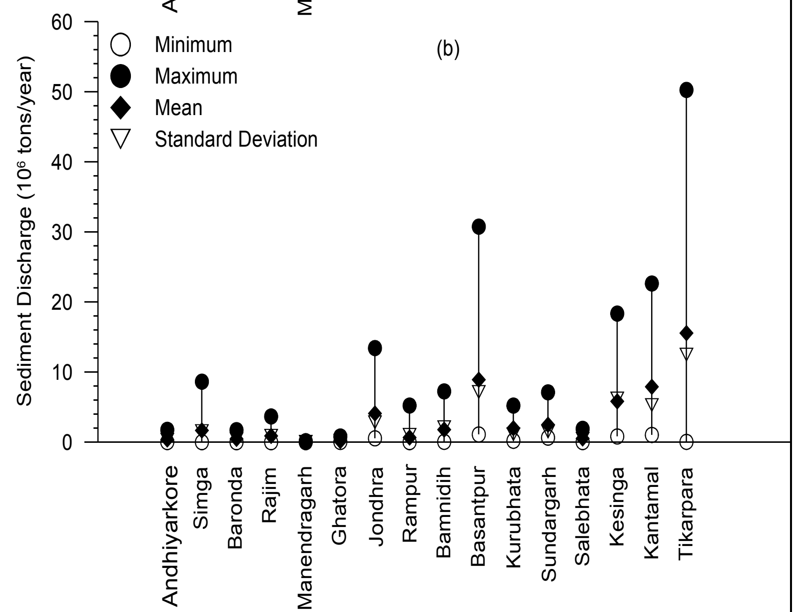
- ✓ **Wide discharge variations** due to retention by dams and convergence of many tributaries
- ✓ **Spatial variation in sediment discharge** due to variation in catchment relief and basin geology, with monsoon sediment load being the major contributor
- ✓ **79% decline in sediment load** between (1973-1983) and (2007-2017) at the last gauging station (Tikarpara)
- ✓ **Significant decreasing trend in sediment flux** in comparison with **non-significant trend in runoff** *(at 5% level of significance)*
- ✓ Coefficient of determination of **sediment rating curves** (i.e., sediment load versus discharge curve) decreases from upstream to downstream
- ✓ **Dams resulted in 65-78% decrease** in mean annual sediment load

Variations of annual runoff & sediment load



(a) Water discharge statistics

- ➢Wide discharge variations due to retention and convergence of many tributaries



(b) Sediment discharge statistics

- ➢Spatial variation due to catchment relief, basin geology
- ➢79% decline in sediment load between (1973-1983) and (2007-2017)
- ➢Monsoon sediment load is the major contributor

Summary of findings

- ✓ **Wide discharge variations** due to retention by dams and convergence of many tributaries
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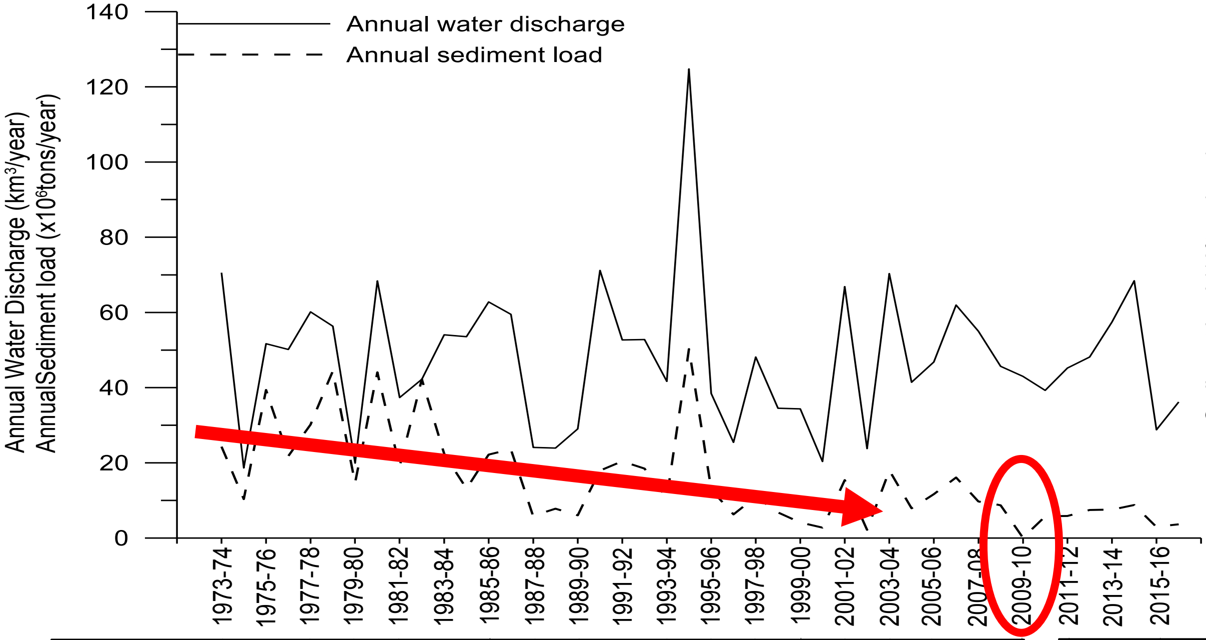
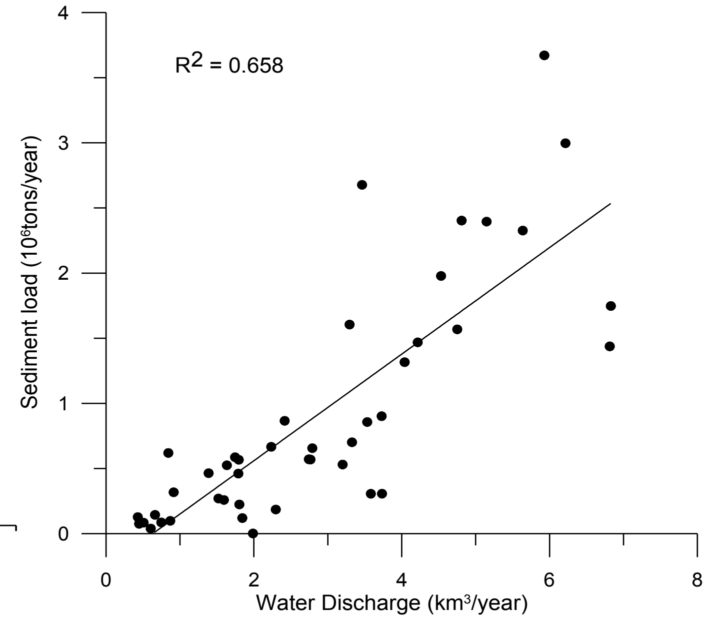
Tikarpara time series



Sediment rating curve



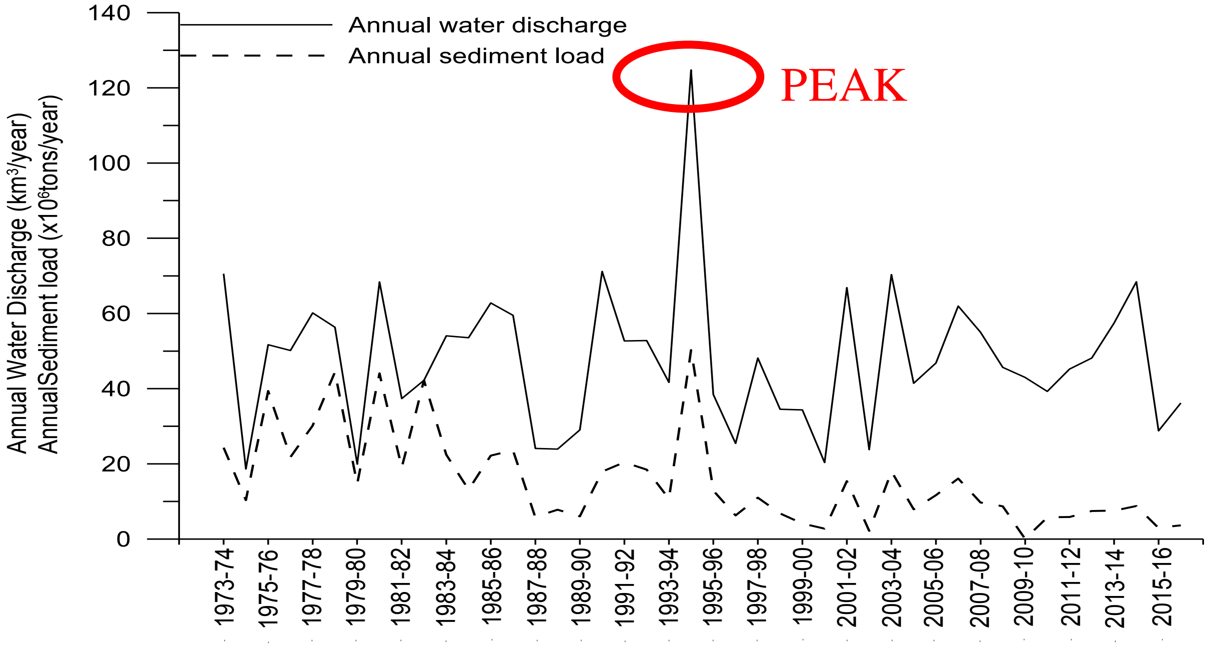
✓ No regular cyclic sequence in **water discharge**

✓ Steady **decrease** of **sediment discharge**, touches almost zero in 2009-10 due to progressive retention of discharge as well as sediment

✓ **Positive correlations** (0.5 -1) at most stations

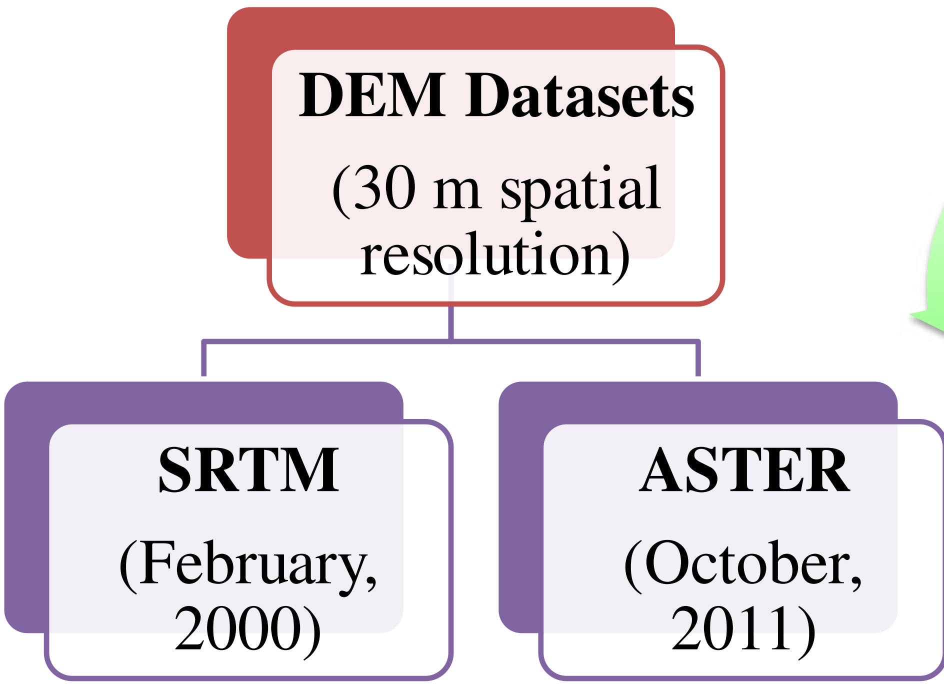
✓ **Correlation coefficient decreases** from upstream to downstream

Tikarpara annual discharge and sediment load time series

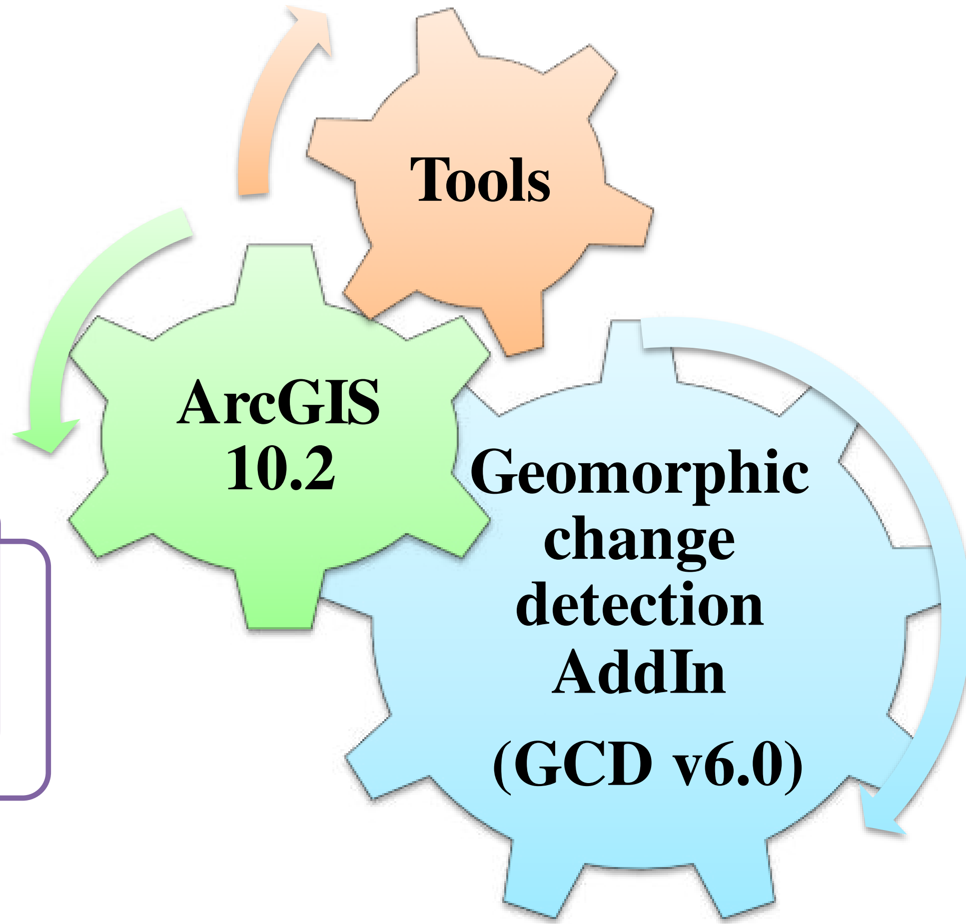


- A **peak in annual water discharge** for the year 1994-95: Due to the **occurrence of a major flood event** in the Odisha hitting almost 25 districts of Mahanadi basin

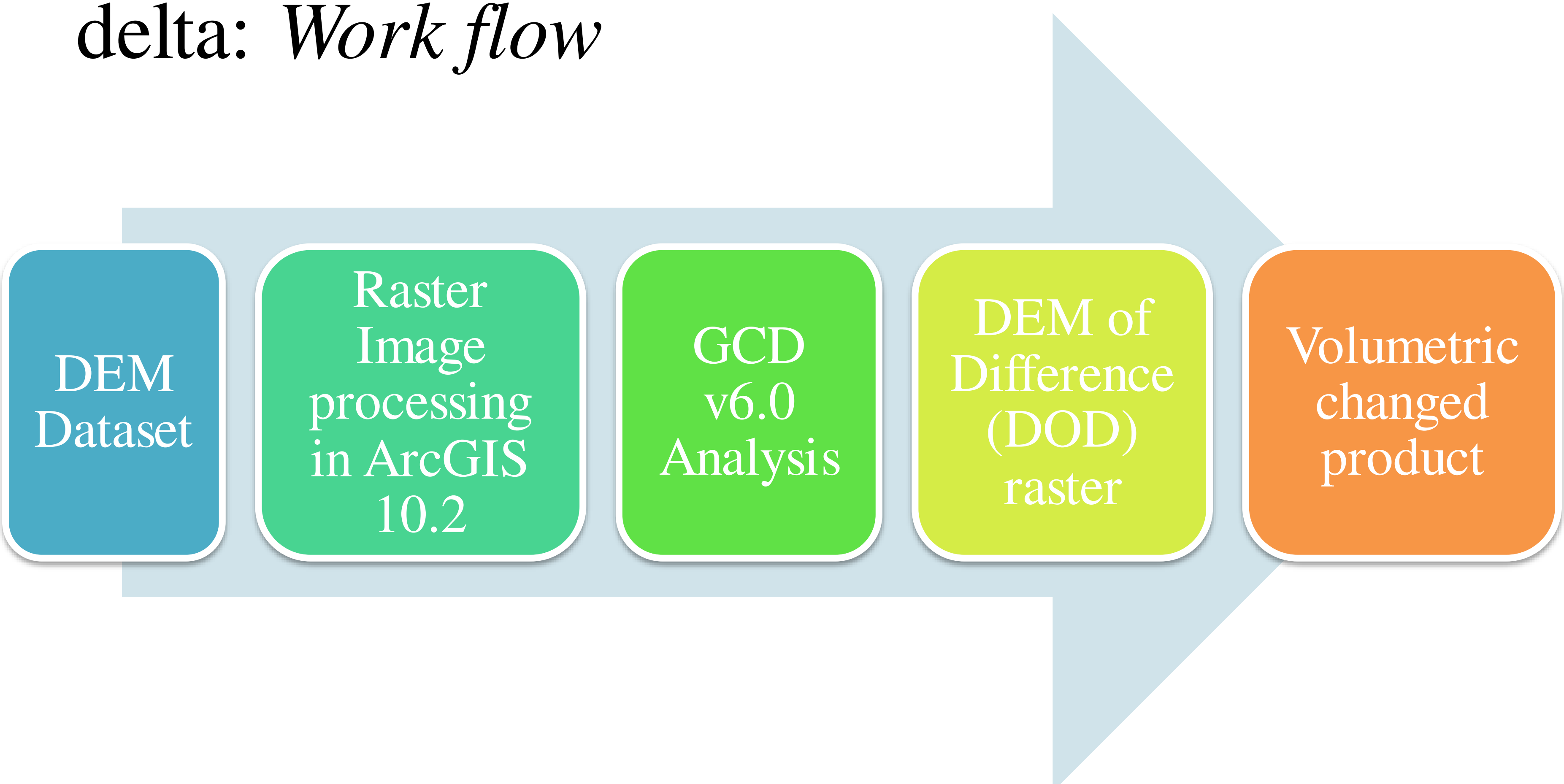
Volumetric change detection of the Mahanadi delta: *Datasets and Tools*



(https://earthexplorer.usgs.gov/)



Volumetric change detection of the Mahanadi delta: *Work flow*



- **Assumption**: A buffer zone of 500 m from the coastline is considered for volumetric change detection, as the marked deltaic response to the temporal change in sediment load from the entire catchment will not extend beyond it

Results of volumetric change analysis (2000-2011)

- **Attributes**: (1) **Areal**-

  Total area of erosion = 11 km^2

  Total area of deposition = 22.7 km^2

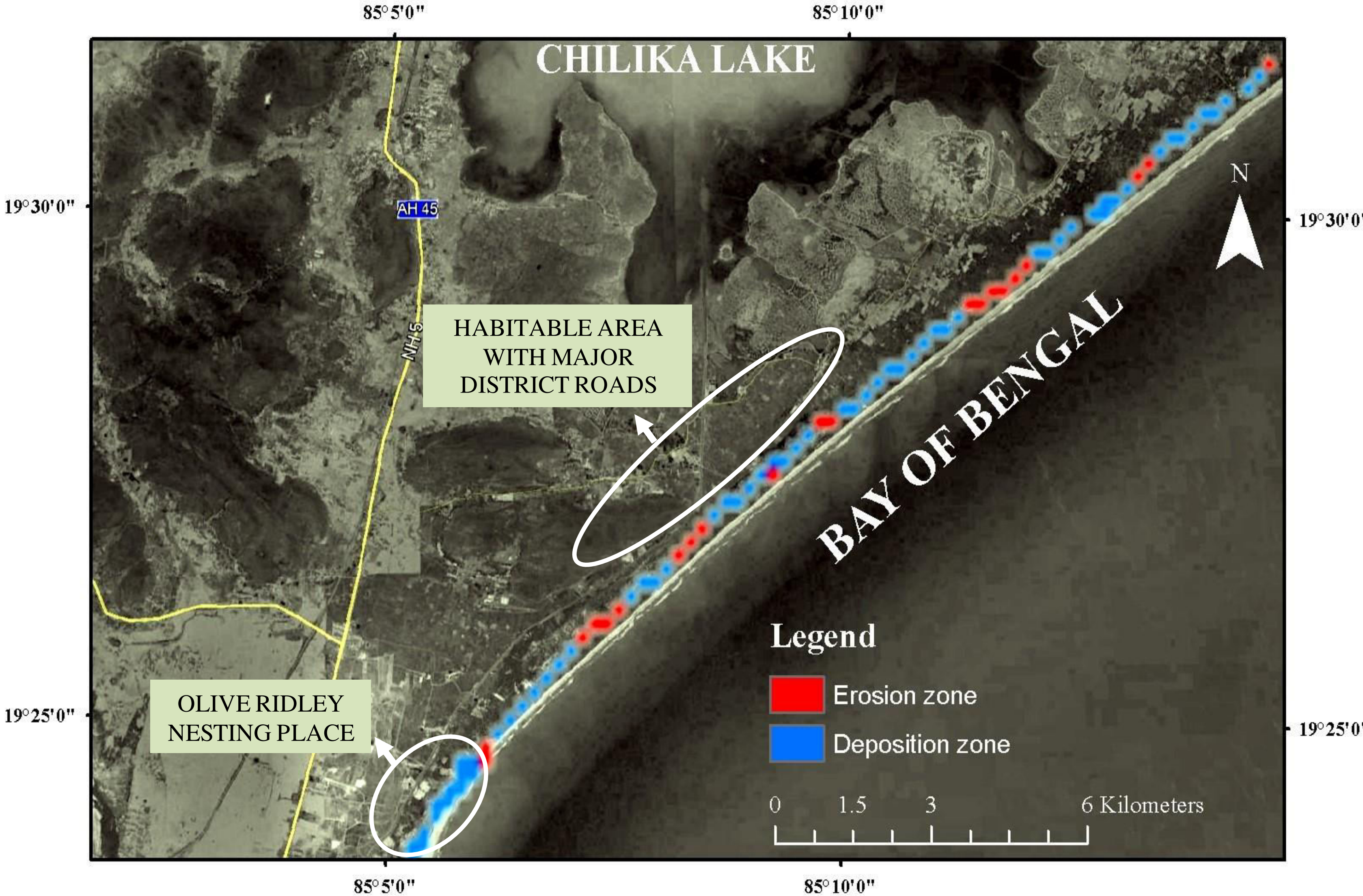
  (2) **Volumetric**-

  Total volume of erosion = 3.9 km^3

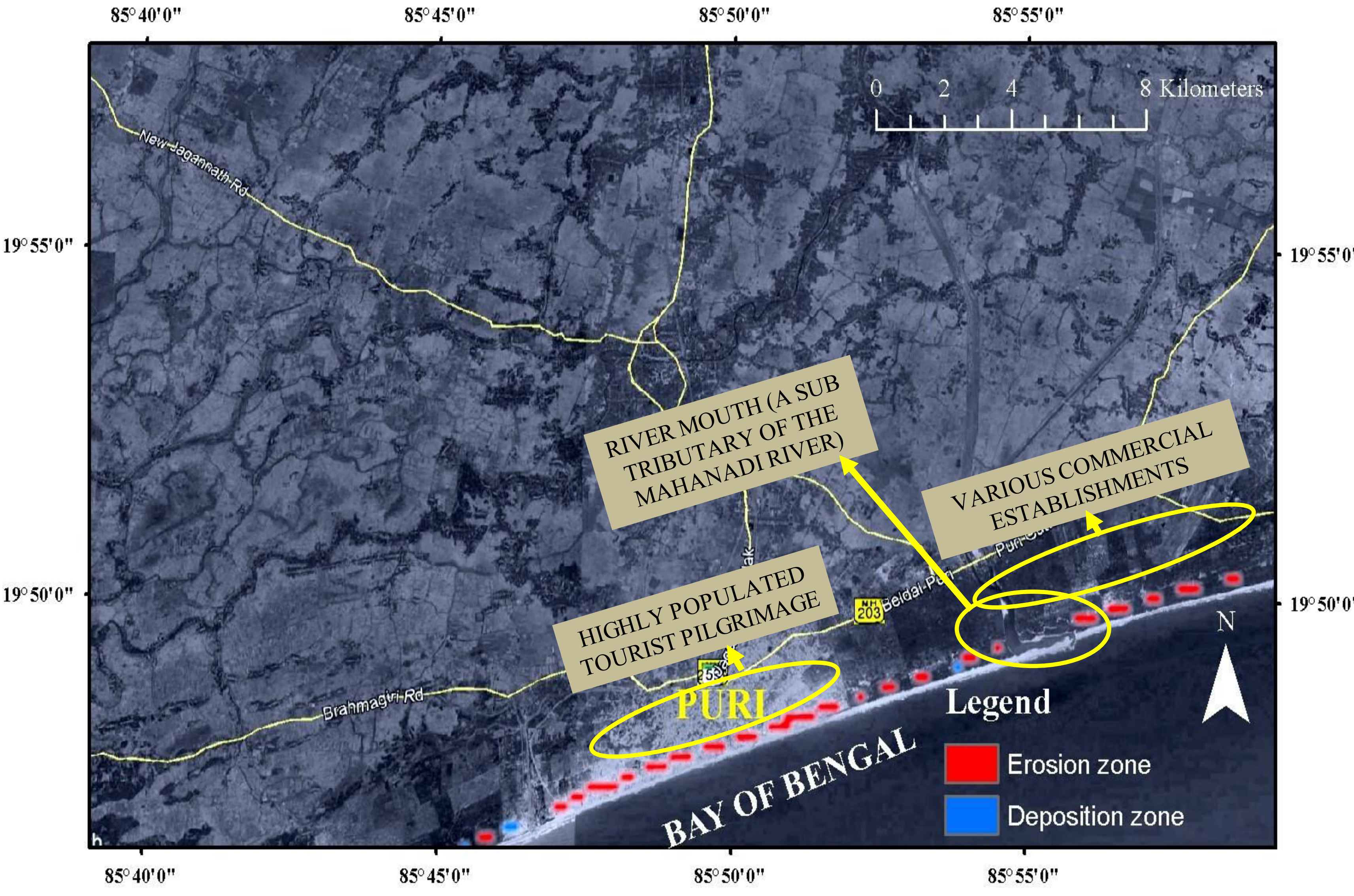
  Total volume of deposition = 0.1 km^3

- Above figures show that the **landforms which are susceptible to erosion are highly vulnerable** as the total volume of land loss exceeds its accretion rate

Map of coastal zone showing significant erosion and deposition areas (2000-2011)

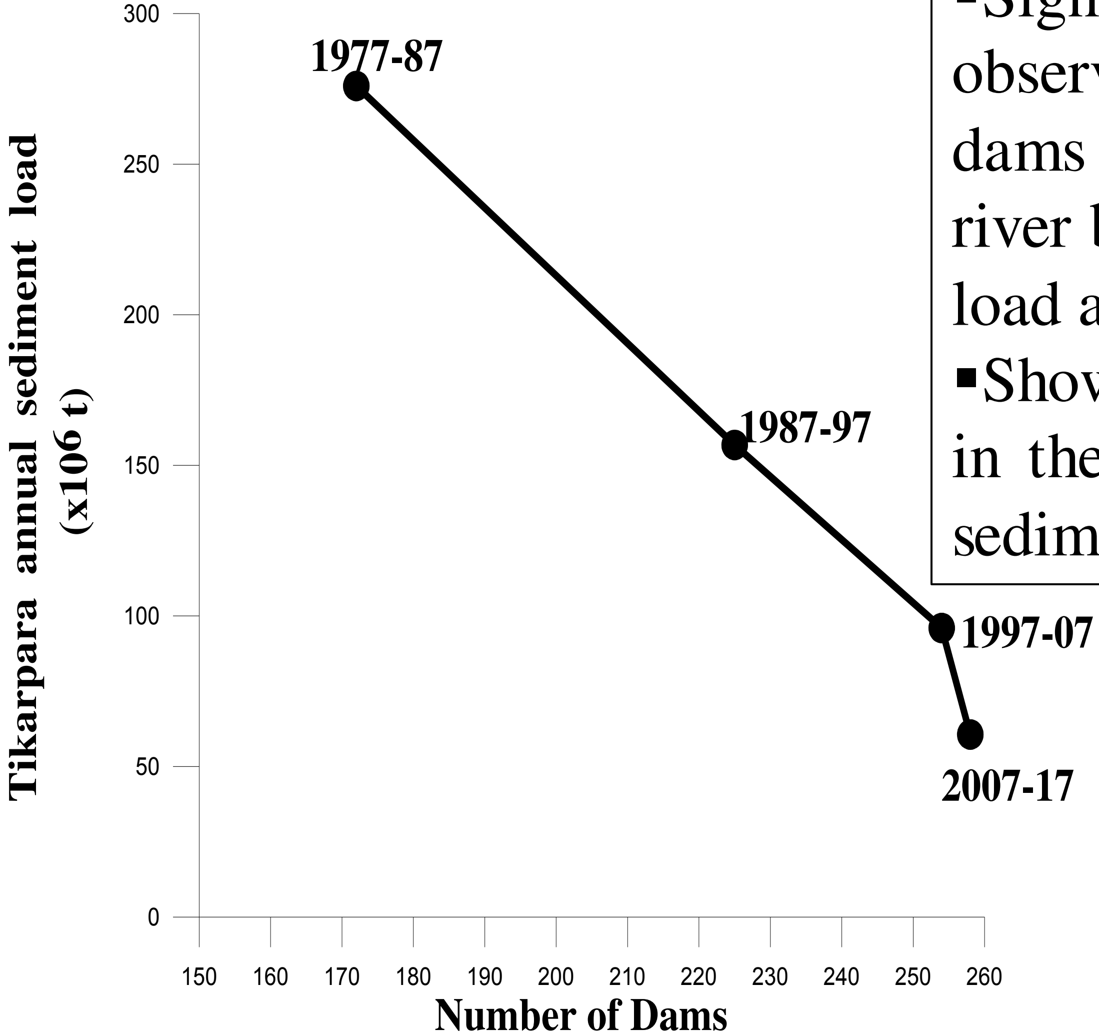


Map of coastal zone showing significant erosion and deposition areas (2000-2011)



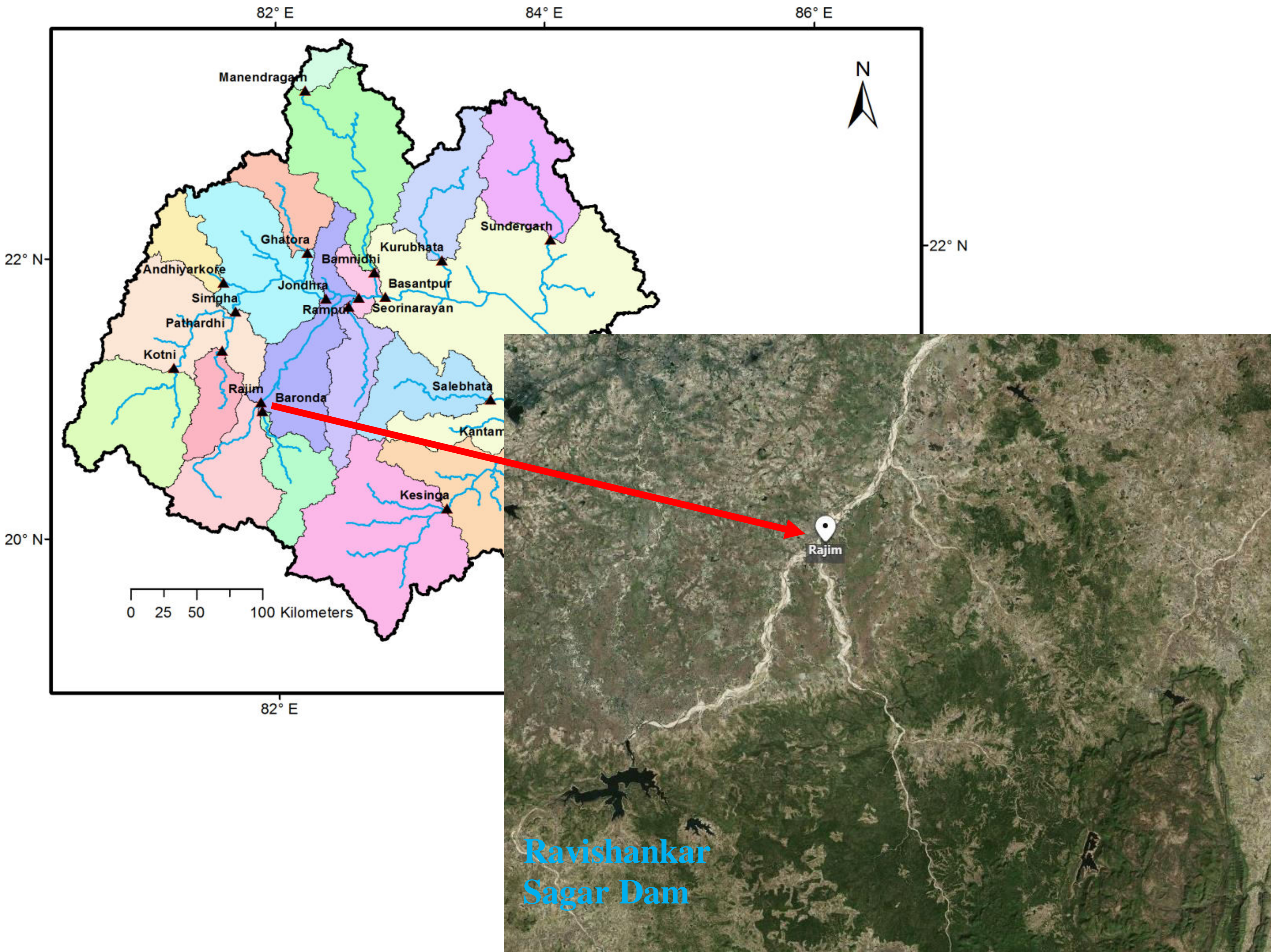
Factors responsible for the reduced sediment load to delta

1. *Effect of the construction of dams in the Mahanadi river basin at decadal scale*

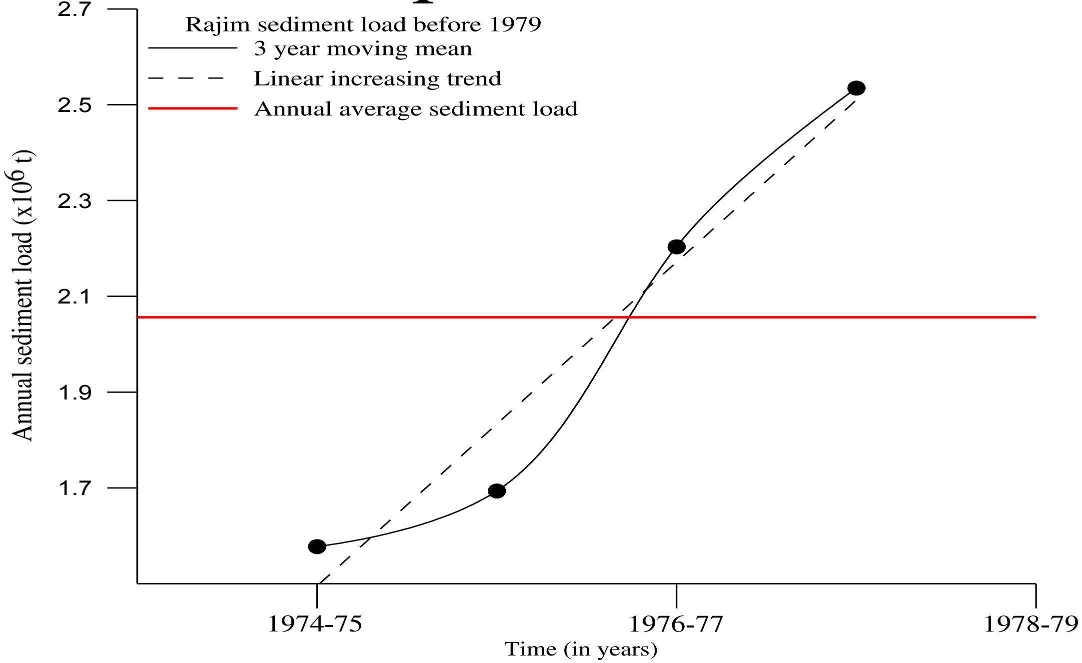


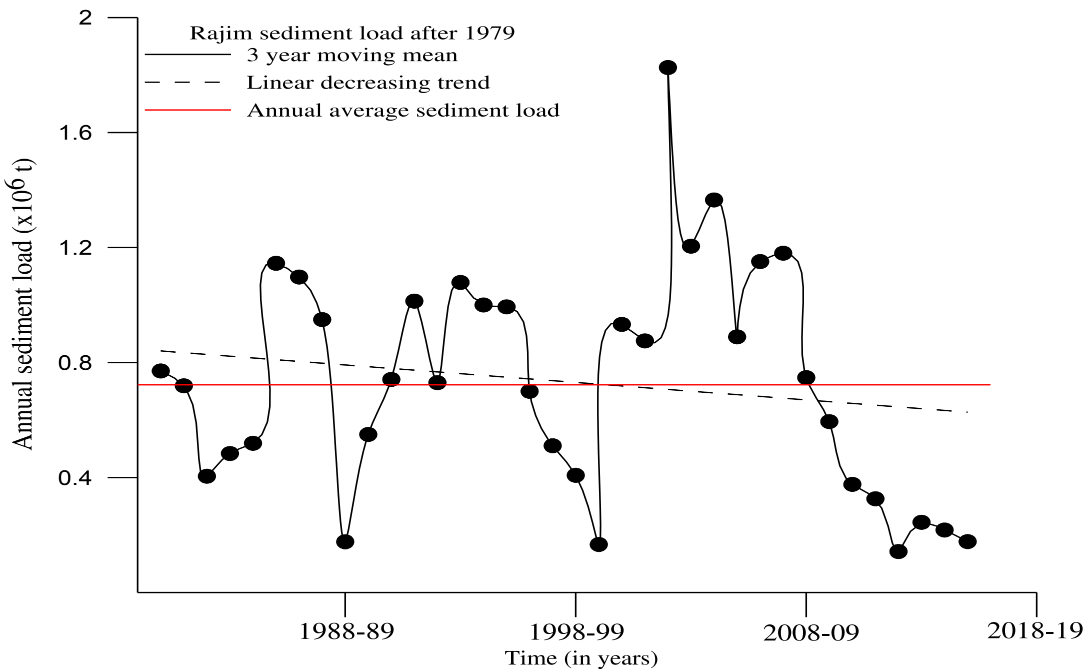
- Significant inverse relation observed between the number of dams constructed in the Mahanadi river basin and the annual sediment load at Tikarpara
- Shows strong influence of dams in the decadal response of annual sediment transport across the basin

Downstream impact on sediment load (at Rajim station) before and after construction of **Ravishankar Sagar Dam** (1979)



Factors responsible … contd.

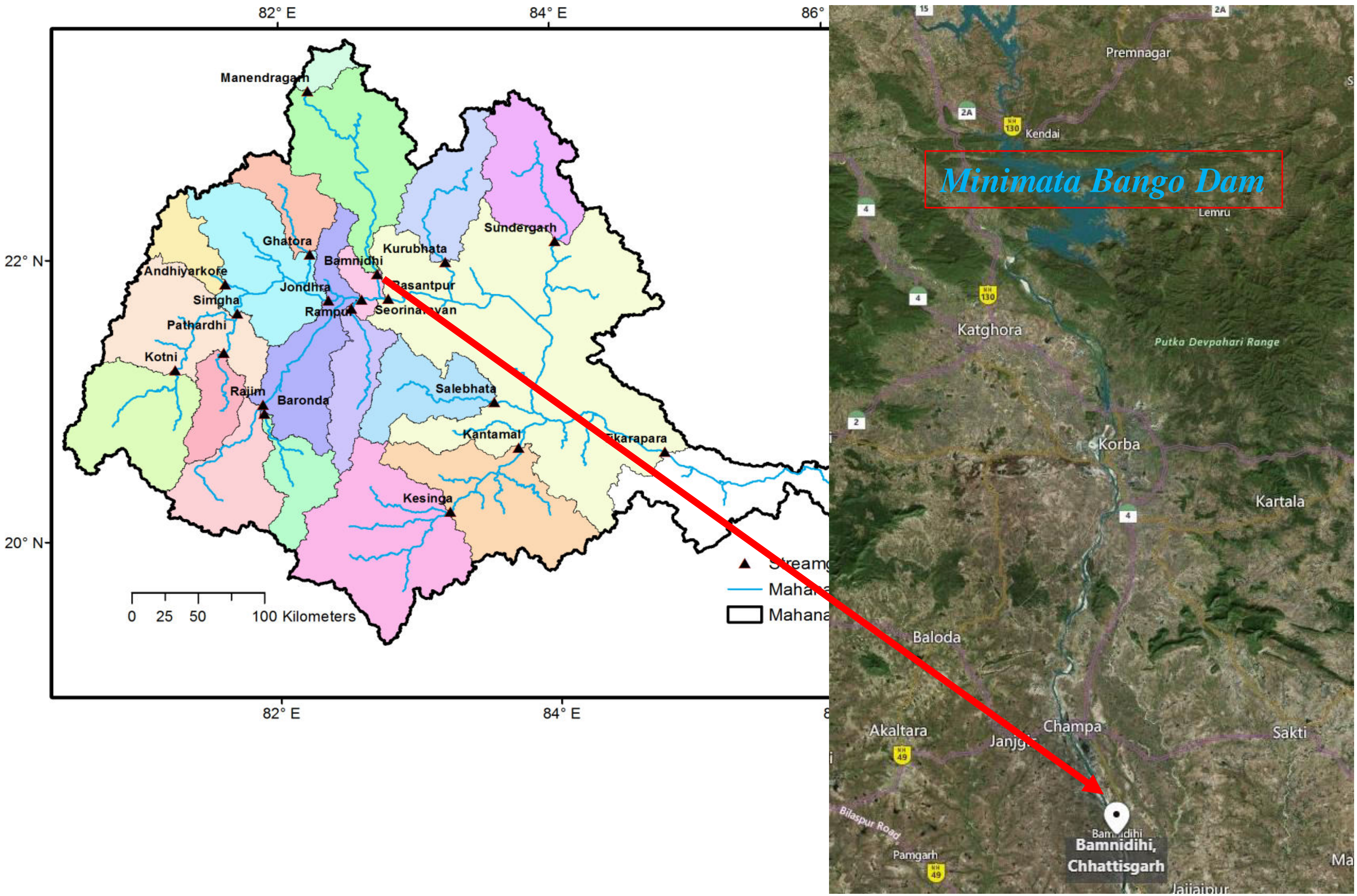




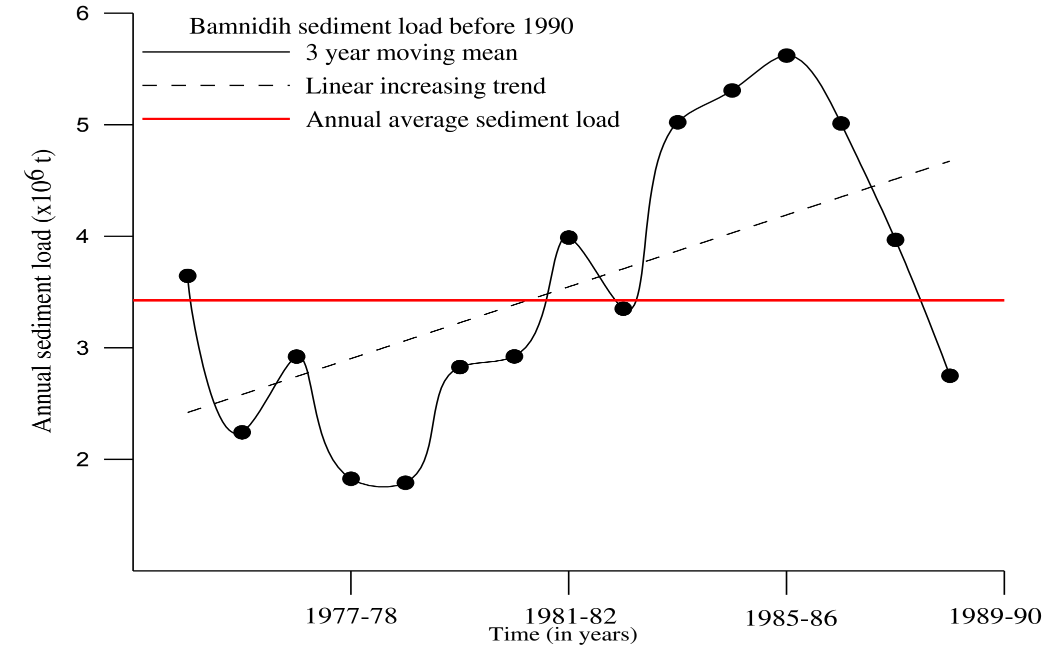
2. Downstream impact on sediment load (at Rajim station) before and after construction of ***Ravishankar Sagar Dam*** *(1979)*

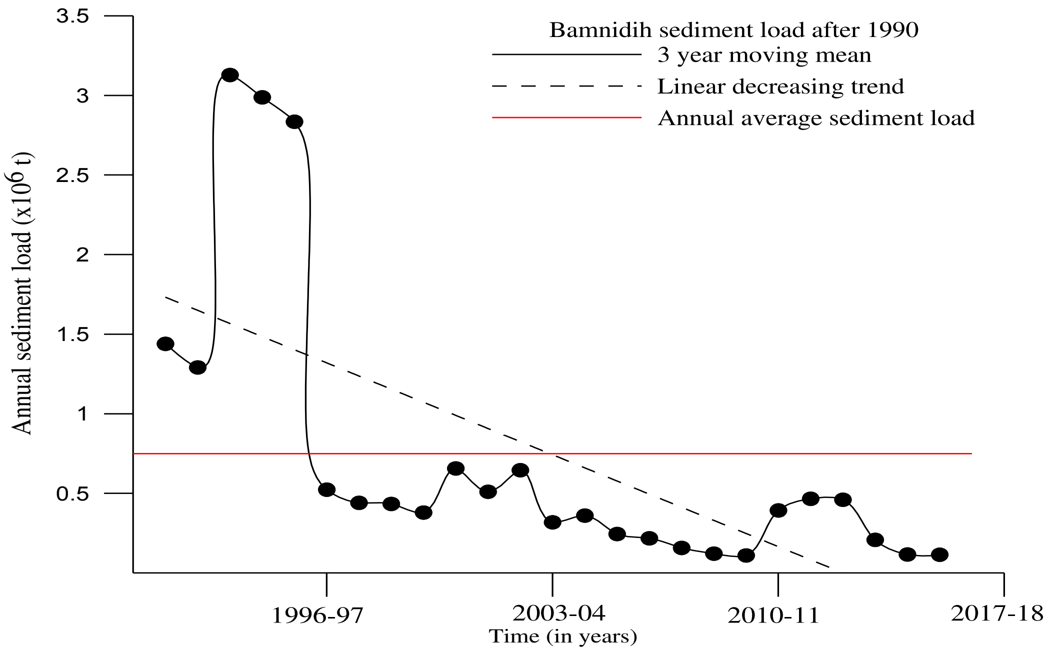
- Increasing trend of annual sediment load before the construction of dam till 1979
- Decreasing trend of annual sediment load observed after the construction of dam in 1979 till 2017
- Shows significant amount of sediments trapped by the reservoir

Downstream impact on sediment load (at Rajim station) before and after construction of **Ravishankar Sagar Dam** (1979)



Factors responsible … contd.





3. Downstream impact on sediment load (at Bamnidih station) before and after construction of ***Minimata Bango Dam*** *(1990)*

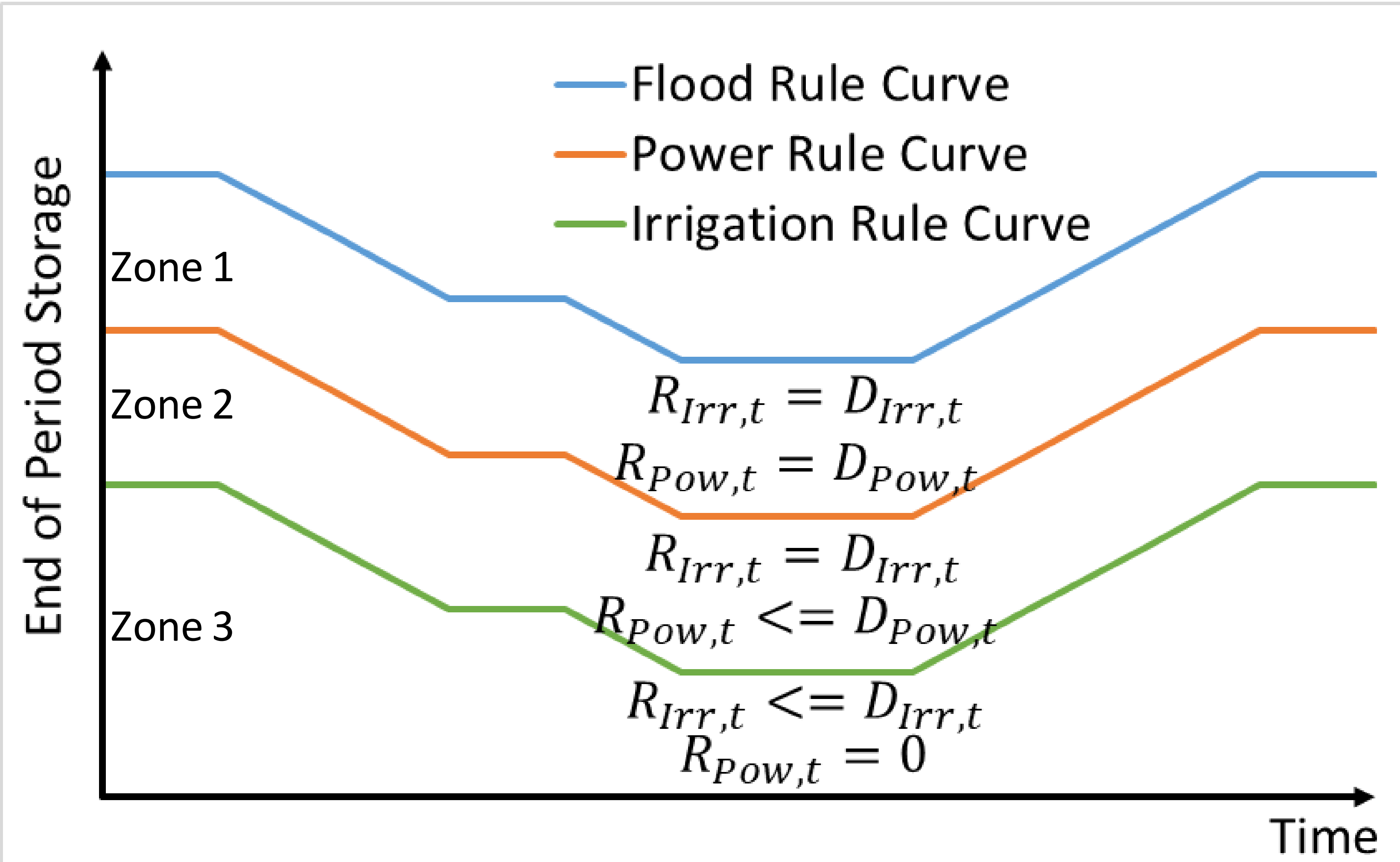
- Similar increasing trend of annual sediment load before the construction of dam till 1990
- Even steeper decreasing trend of annual sediment load observed after the construction of dam in 1999 till 2017
- Shows huge amount of sediments being sequestered by the reservoir

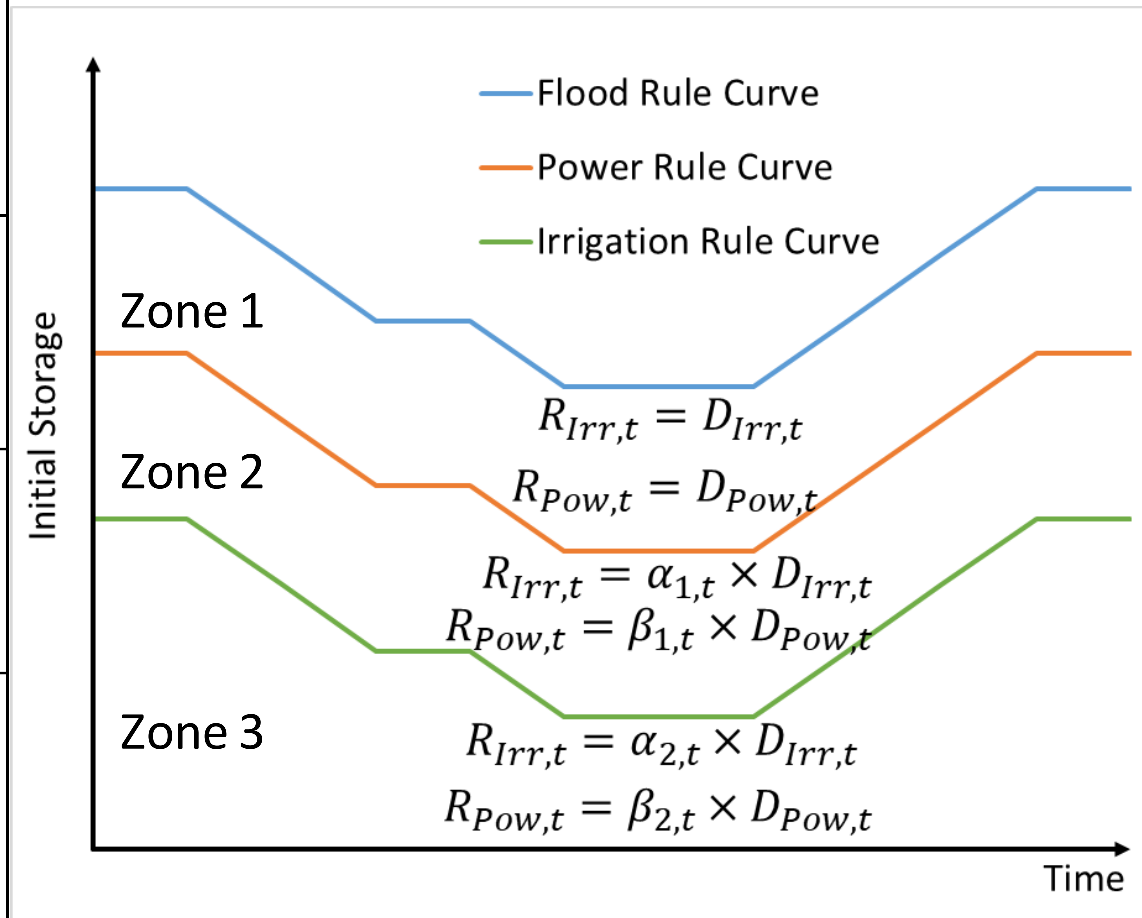
Mapping of Milestones/activities

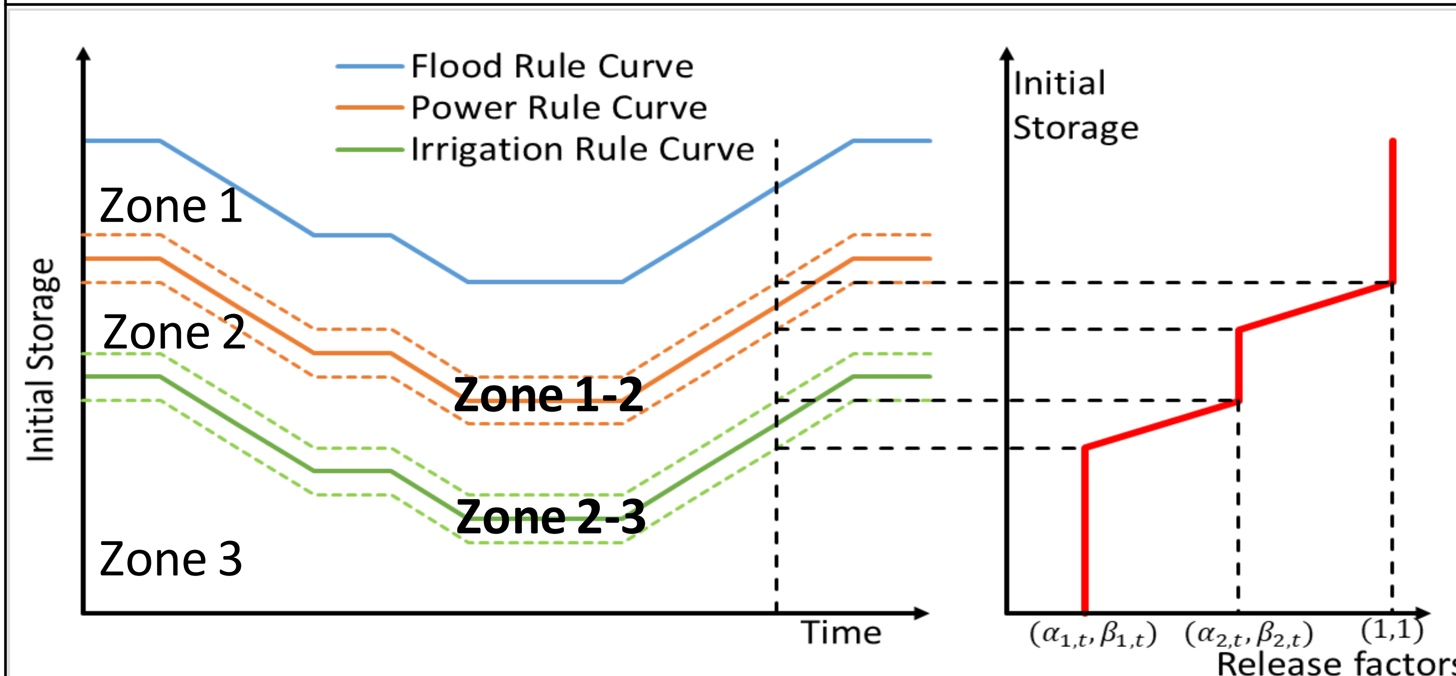
Sl. No	Milestone/ Activity	Time in Months											
		0 to 3	3 to 6	6 to 9	9 to 12	12 to 15	15 to 18	18 to 21	21 to 24	24 to 27	27 to 30	30 to 33	33 to 36
14	Determining future projections of irrigation water demands at Hirakud reservoir for various climate change scenarios, and the corresponding operating policies									■	■	■	
15	Assessing implication of historical and future sediment load on capacity of Hirakud reservoir										■	■	
16	Final Report Preparation												■

(to be undertaken by all Investigators; by Investigators at IISc; by Investigator at IITBBs)

Hedging Based Operation of a Multi-Purpose Reservoir


Flood Rule Curve
Power Rule Curve
Irrigation Rule Curve
End of Period Storage
Zone 1
Zone 2
Zone 3
$R_{Irr,t} = D_{Irr,t}$
$R_{Pow,t} = D_{Pow,t}$
$R_{Irr,t} = D_{Irr,t}$
$R_{Pow,t} <= D_{Pow,t}$
$R_{Irr,t} <= D_{Irr,t}$
$R_{Pow,t} = 0$
Time

Authors	Description	Graphical Representation
Tu et al. (2003)	Hedging factors are prescribed Mixed Integer Linear Programming.	
Chang et al. (2005)	Hedging factors are prescribed Genetic Algorithms for optimization.	
Tu et al. (2008)	Hedging factors are also optimized Mixed Integer Non-Linear Programming.	
Guo et al. (2013)	Hedging factors are also optimized Non-dominated Sorting Particle Swarm Optimization.	

Authors	Description and graphical representation
Ahmadianfar et al. (2016a) (2016b) Shiau et al. (2018)	Hedging factors are also optimized. Hedging factors are transitioned smoothly by transition rule curves. Evolutionary algorithms used for optimization. 

Hirakud Reservoir

Month	Mean Monthly Flows (Million m^3)	Irrigation Demand (Million m^3)	Hydropower Demand (Million m^3)	Normal Pan Evaporation (m)
Jun	1466.1	75	600	0.0633
Jul	8864.6	215	1500	0.0863
Aug	12539.5	227	2000	0.1288
Sep	8356.3	260	2000	0.1845
Oct	2324.5	294	1200	0.2030
Nov	590.0	81	1000	0.1587
Dec	349.6	119	900	0.0836
Jan	181.1	223	600	0.0784
Feb	134.5	244	600	0.0893
Mar	95.0	295	600	0.0962
Apr	48.6	286	600	0.0750
May	25.0	65	600	0.0635

Hirakud Reservoir

- Located on Mahanadi River, Orissa
- Majorly constructed for flood mitigation
- Also Serves Water Supply, Irrigation, Hydropower and Industrial purpose.
- Irrigation through right bank and left bank canals
  - Command area of 157018 ha during kharif and 109912 ha in Rabi season
- Hydropower through a dam power house at Burla and Canal power house (PH) at Chiplima
  - PH at Burla has an installed capacity of 275.5 MW
  - PH at Chiplima has an installed Capacity of 72 MW
  - Tail water from Burla PH is carried to Chiplima PH through a power canal of capacity 510 Mm^3.

- Flood mitigation is primary objective and it is governed by considering the storages specified by the Upper Rule Curve as carryover storage targets.
- Water supply demands and Industrial demands are small and are clubbed with Irrigation demands.
- Irrigation demands and Power demands are known in terms of volumetric units.
- Since Burla and Chiplima power houses are operating independently post restructuring in 2009, only Burla PH is considered for power generation in this case example.

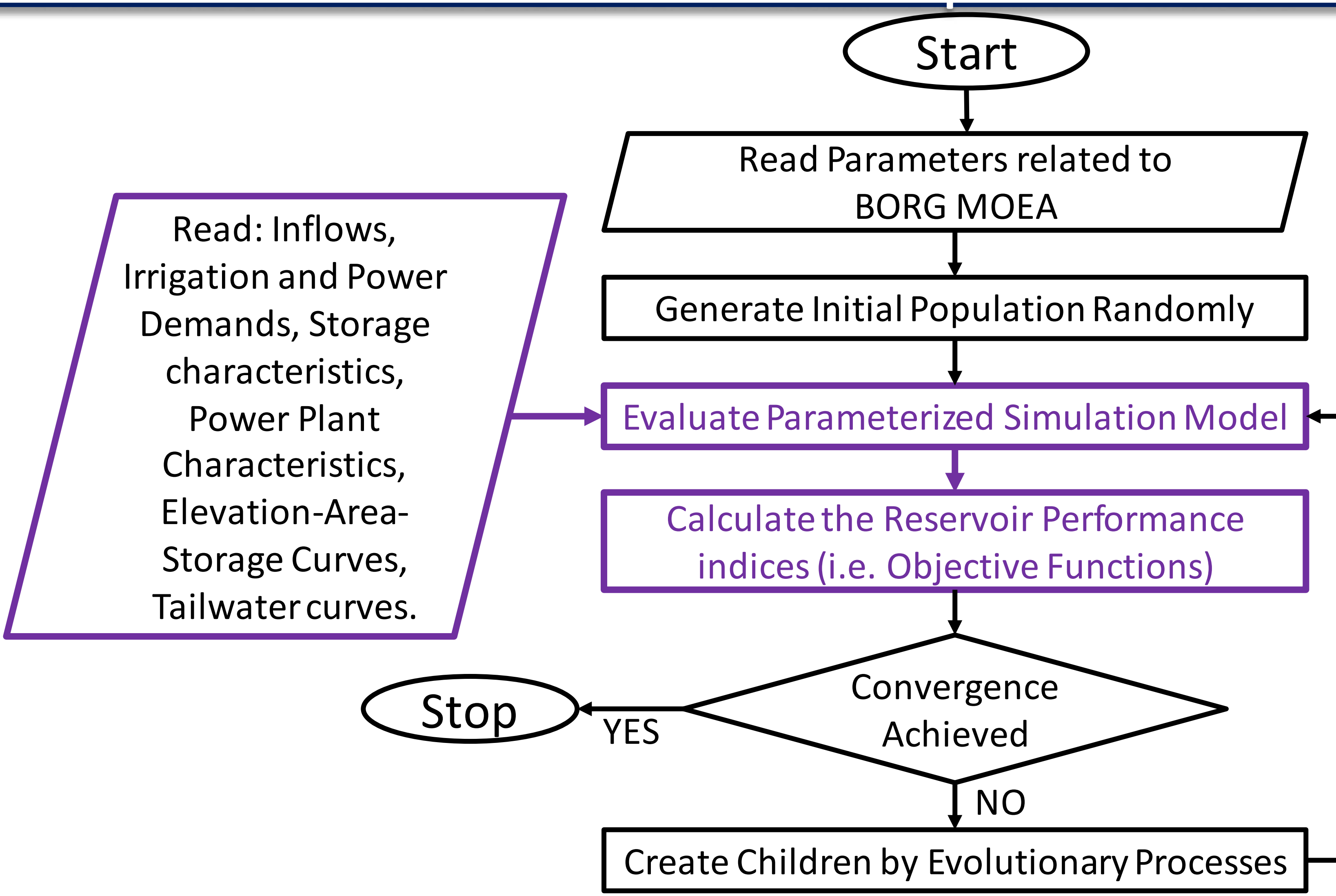
- To derive an Optimal Reservoir Policy, a Parameterization-simulation-optimization (Koutsoyannis and Economou, 2003) or Direct Policy Search framework (Giuliani et al. 2016) is adopted.
- Each Parameterized simulation model is coupled with BORG Multi Objective Evolutionary Algorithm (BORG MOEA) (Hadka and Reed, 2013).
- The Modified Shortage Index (Hsu and Cheng 2002; Taghian et al. 2014) is adopted as objective function to drive the search for Optimal Reservoir Policy.

$$MSI = \frac{100}{NP} \times \sum_{t=1}^{NP} \left(\frac{Deficit_t}{Demand_t} \right)^2$$

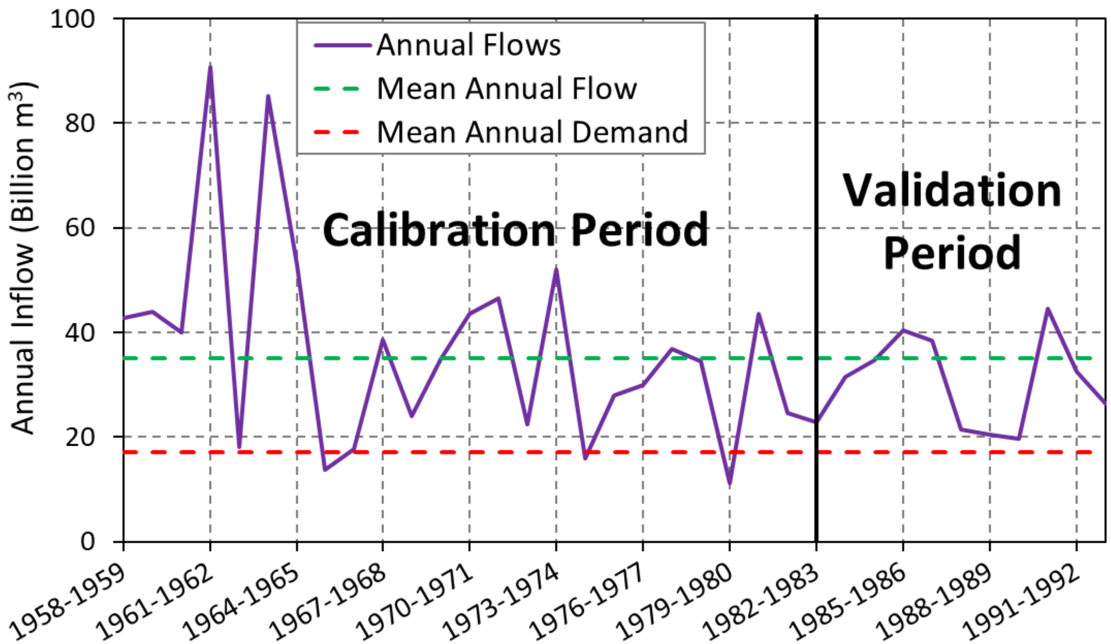
- The decision variables which describe the release, i.e Rule curve storages (RCO, RCH and FRCH), and/or Hedging factors (RCH and FRCH) are parameterized on monthly scale.
- For example, supposing $x_{i,j}^{k}$ is one of the decision variable, it is parameterized as

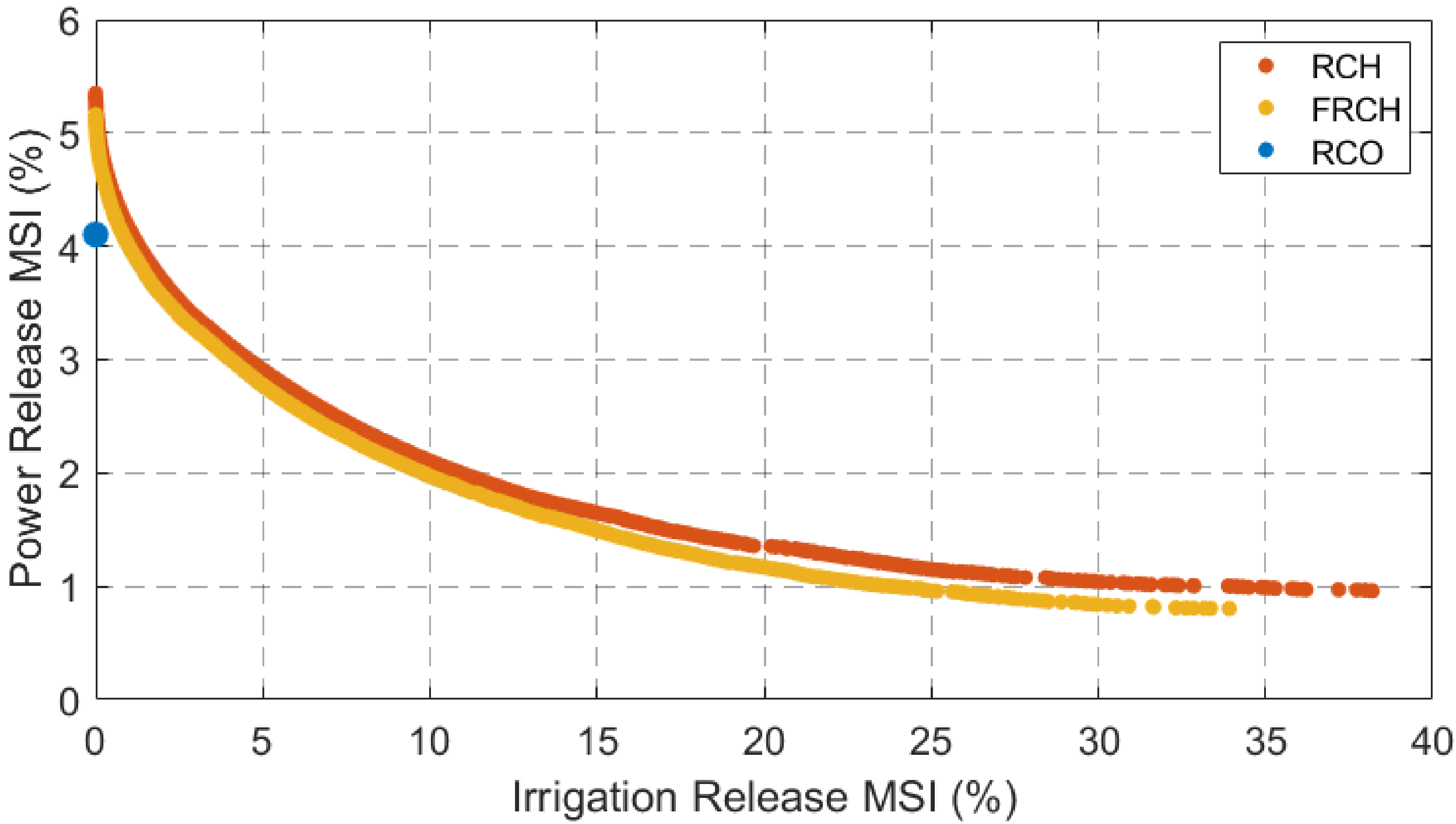
$$x_{i,j}^{k} = a_{i}^{k} \; \forall \; k = 1,2, \ldots nDVs; i = 1,2, \ldots 12 \; and \; j = 1,2, \ldots n \; Years$$

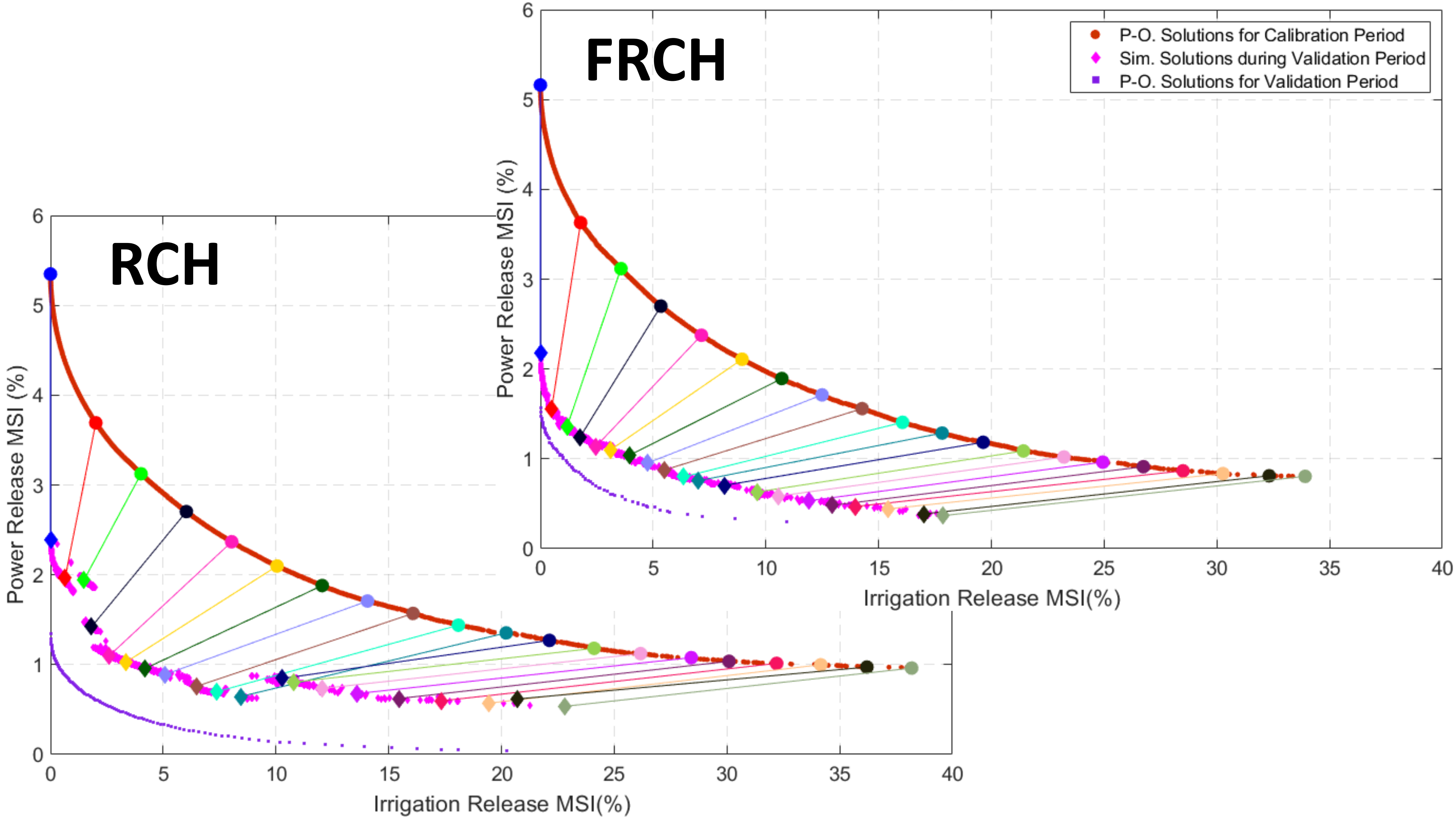
- This ensures the release policy is changing from one month to another, while it is same for a given month in any given year.


Start
Read Parameters related to BORG MOEA
Generate Initial Population Randomly
Read: Inflows, Irrigation and Power Demands, Storage characteristics, Power Plant Characteristics, Elevation-Area-Storage Curves, Tailwater curves.
Evaluate Parameterized Simulation Model
Calculate the Reservoir Performance indices (i.e. Objective Functions)
Convergence Achieved
Stop
YES
NO
Create Children by Evolutionary Processes

- Out of the 35 years of Inflow Data (1958-1993) available, the first 25 years of data is considered for calibrating and a Pareto-Optimal (PO) front is obtained between irrigation and Power.
- The Last 10 Years of Data is used for validation.
- Since no benchmark releases are available for validation, the optimization model is executed for the last 10 years separately so as to get a P-O front for that period.




RCH
FRCH
RCO
Power Release MSI (%)
Irrigation Release MSI (%)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40


FRCH
RCH
P-O. Solutions for Calibration Period
Sim. Solutions during Validation Period
P-O. Solutions for Validation Period
Power Release MSI (%)
Irrigation Release MSI(%)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40

Ahmadianfar, I., Adib, A., and Taghian, M. (2016). “Optimization of Fuzzified Hedging Rules for Multipurpose and Multireservoir Systems.” *Journal of Hydrologic Engineering*, 21(4), 05016003.

Chang, F. J., Chen, L., and Chang, L. C. (2005). “Optimizing the reservoir operating rule curves by genetic algorithms.” *Hydrological Processes*, 19(11), 2277–2289.

Giuliani, M., Castelletti, A., Pianosi, F., Mason, E., and Reed, P. (2016). “Curses, Tradeoffs, and Scalable Management: Advancing Evolutionary Multiobjective Direct Policy Search to Improve Water Reservoir Operations.” *Journal of Water Resources Planning and Management*, 142(2), 4015050.

Guo, X., Hu, T., Zeng, X., and Li, X. (2013). “Extension of Parametric Rule with the Hedging Rule for Managing Multi-Reservoir System during Droughts.” *Journal of Water Resources Planning and Management*, 139(2), 139–148.

Hadka, D., and Reed, P. (2013). “Borg: An Auto-Adaptive Many-Objective Evolutionary Computing Framework.” *Evolutionary Computation*, 21(2), 231–259.

Shiau, J.-T., Hung, Y.-N., and Sie, H.-E. (2018). “Effects of Hedging Factors and Fuzziness on Shortage Characteristics During Droughts.” *Water Resources Management*, Water Resources Management, 32(5), 1913–1929.

Shiau, J.-T., Hung, Y.-N., and Sie, H.-E. (2018). “Effects of Hedging Factors and Fuzziness on Shortage Characteristics During Droughts.” *Water Resources Management*, Water Resources Management, 32(5), 1913–1929.

Taghian, M., Rosbjerg, D., Haghighi, A., and Madsen, H. (2014). “Optimization of Conventional Rule Curves Coupled with Hedging Rules for Reservoir Operation.” *Journal of Water Resources Planning and Management*, 140(5), 693–698.

Tu, M.-Y., Hsu, N.-S., and Yeh, W. W.-G. (2003). “Optimization of Reservoir Management and Operation with Hedging Rules.” *Journal of Water Resources Planning and Management*, 129(2), 86–97.

Tu, M.-Y., Hsu, N.-S., Tsai, F. T.-C., and Yeh, W. W.-G. (2008). “Optimization of Hedging Rules for Reservoir Operations.” *Journal of Water Resources Planning and Management*, 134(1), 3–13.

THANK YOU

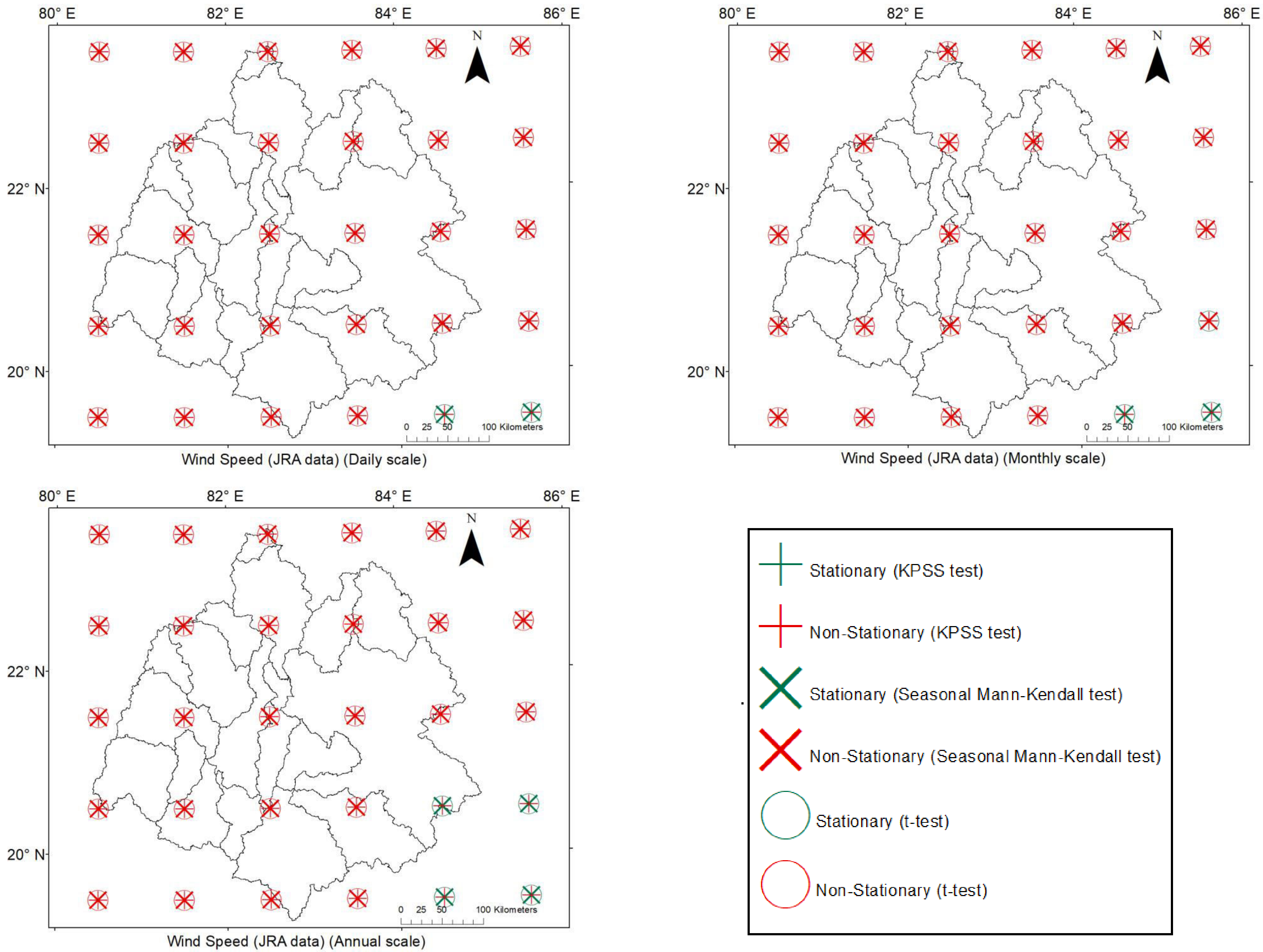
Deliverables

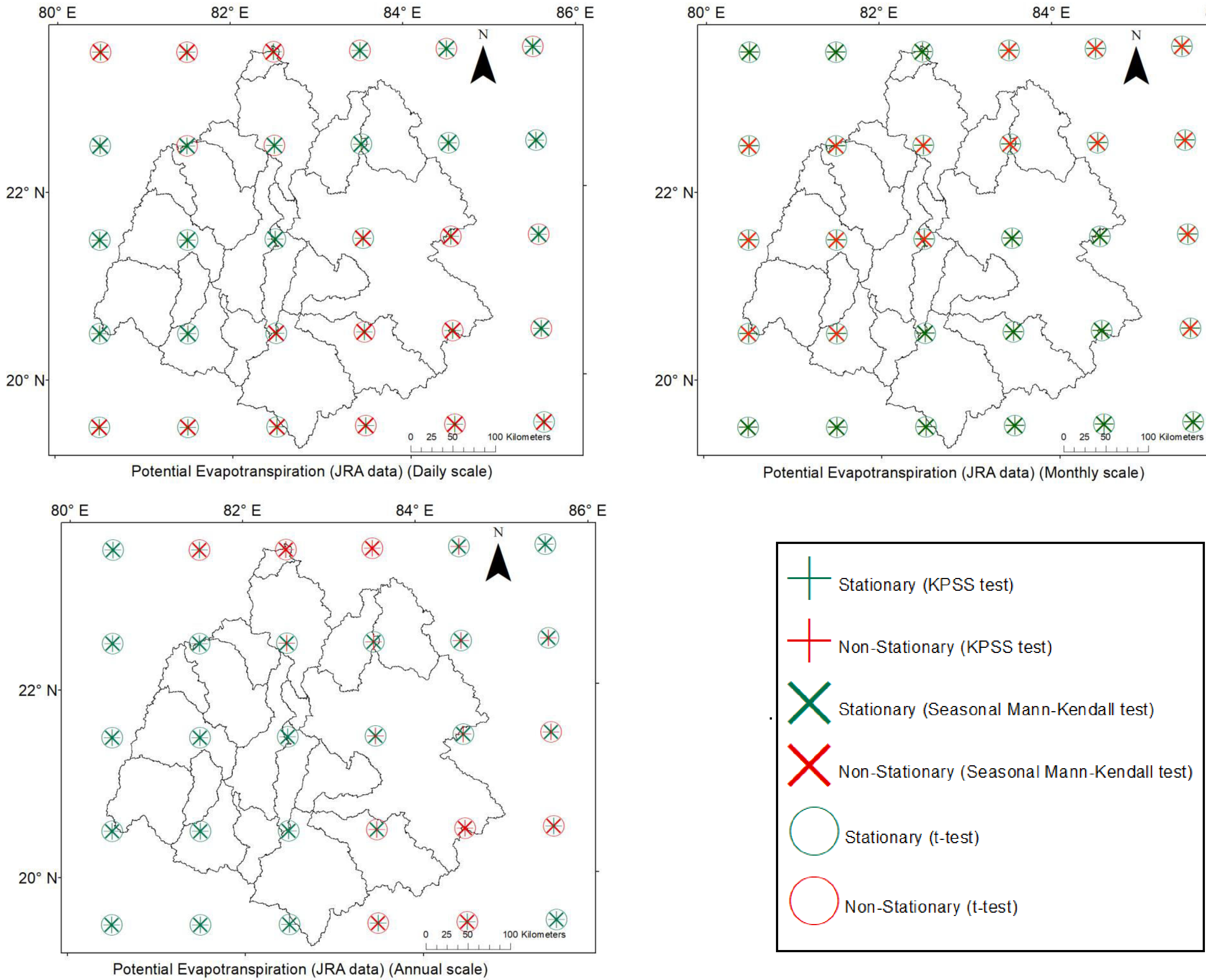
Deliverables that are expected from the project are as follows:

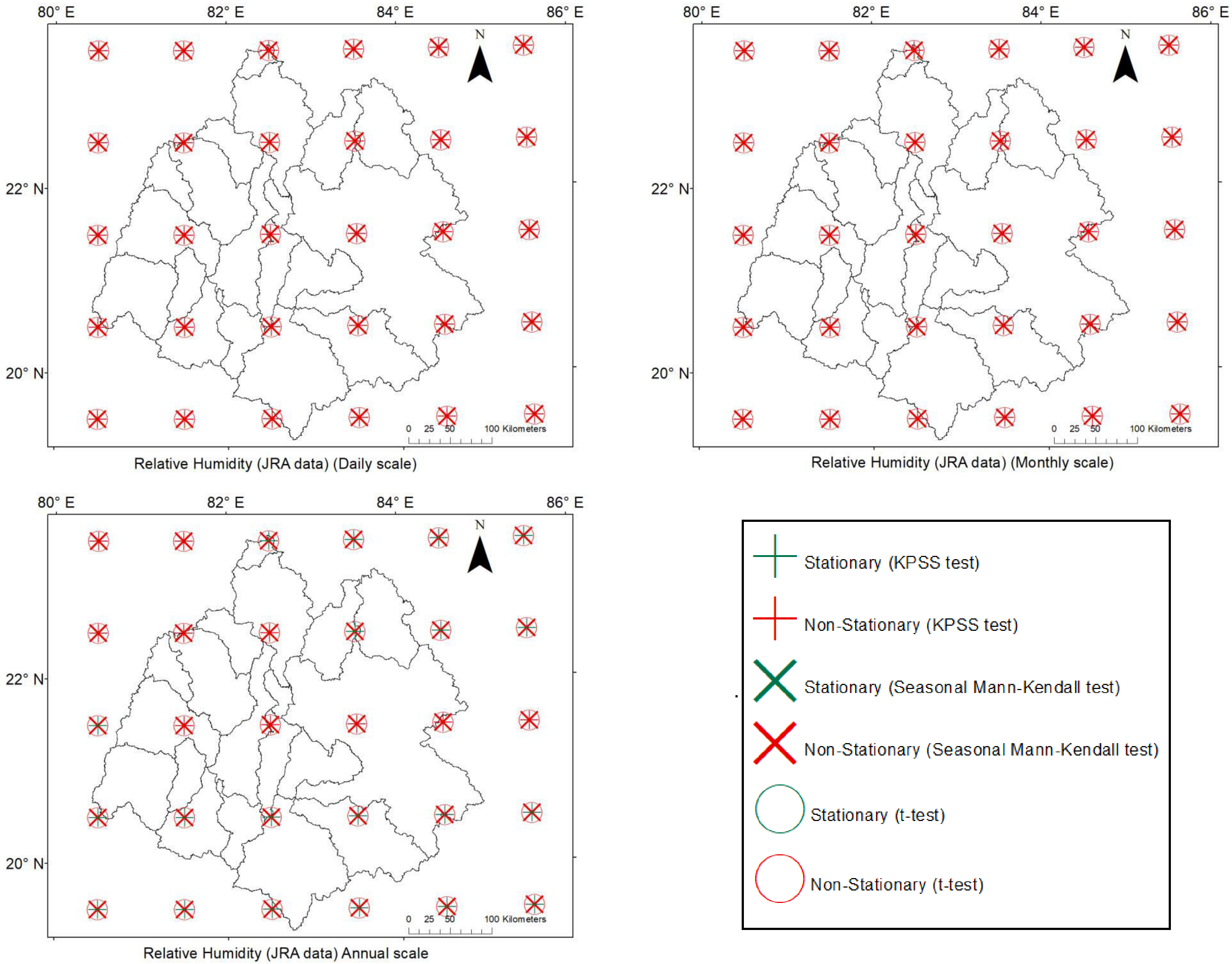
1. Review of literature on past studies and methodologies considered for addressing the objectives that are of interest to the present study,
2. Details of data and data sources for the Mahanadi river basin and interpretations drawn based on base line analysis of the data (i.e., key statistics, data gaps),
3. Results of parametric and non-parametric tests for trend detection in observed meteorological and hydrological variables and basin sediment yield data, and interpretations drawn based on the analysis,
4. Calibrated and validated hydrological model(s) for the river basin, and discerned relationships between various components of hydrological cycle (i.e., water balance components) in the basin for the baseline (historical) period,
5. Model establishing a relationship between the suspended and bed sediment transport and the discharge in the Mahanadi river for the baseline period, and estimates of annual sediment yield in the basin,
6. Future (projected) downscaled scenarios of hydrological processes (including streamflows) in the river basin,
7. Impacts of climate change on water availability at various critical gauged as well as ungauged sites (hot spots) in the Mahanadi basin in terms of change in flow duration curves,

Deliverables

8. Future scenarios of sediment load at various locations in Mahanadi basin and their trend,
9. Impacts of climate change on reservoir capacity of Hirakud dam in the river basin, owing to sediment deposition,
10. Historical scenarios of hydrological extremes (including extreme rainfall, floods, and droughts) in the Mahanadi basin based on the base line data, and equations developed to estimate their magnitude corresponding to various frequencies at gauged as well as ungauged target locations (hot spots) in the river basin,
11. Impacts of climate change on meteorological/hydrologic droughts (in terms of change in frequencies of occurrence), and analysis of uncertainties in the impacts,
12. Impacts of climate change on extreme rainfall and floods in the basin at the identified hot spots, in terms of change in magnitude corresponding to various frequencies, and their uncertainties for the near-future (2015-2040) and for distant future (2040-2100) periods,
13. Future scenarios of irrigation water demands at Hirakud reservoir,
14. Operation policies for the Hirakud reservoir corresponding to the current and climate change scenarios,
15. Recommendations for adaptation measures/options to mitigate adverse impacts of climate changes in the river basin, and
16. Organisation of training course/workshop


80° E
82° E
84° E
86° E
22° N
20° N
N
0 25 50 100 Kilometers
Wind Speed (JRA data) (Daily scale)
Wind Speed (JRA data) (Monthly scale)
Wind Speed (JRA data) (Annual scale)
Stationary (KPSS test)
Non-Stationary (KPSS test)
Stationary (Seasonal Mann-Kendall test)
Non-Stationary (Seasonal Mann-Kendall test)
Stationary (t-test)
Non-Stationary (t-test)


80° E
82° E
84° E
86° E
22° N
20° N
N
0 25 50 100 Kilometers
Potential Evapotranspiration (JRA data) (Daily scale)
Potential Evapotranspiration (JRA data) (Monthly scale)
Potential Evapotranspiration (JRA data) (Annual scale)
Stationary (KPSS test)
Non-Stationary (KPSS test)
Stationary (Seasonal Mann-Kendall test)
Non-Stationary (Seasonal Mann-Kendall test)
Stationary (t-test)
Non-Stationary (t-test)


80° E
82° E
84° E
86° E
22° N
20° N
N
0 25 50 100 Kilometers
Relative Humidity (JRA data) (Daily scale)
Relative Humidity (JRA data) (Monthly scale)
Relative Humidity (JRA data) Annual scale
Stationary (KPSS test)
Non-Stationary (KPSS test)
Stationary (Seasonal Mann-Kendall test)
Non-Stationary (Seasonal Mann-Kendall test)
Stationary (t-test)
Non-Stationary (t-test)