Geo-informatics of Sedimentation in Indravati Reservoir, Odisha

Abstract

The Indravati Basin, in S-W Odisha, with catchment of 38306 Sq. Km. houses the complex Upper Indravati Project (UIP) comprising of four dams, eight dykes, a power house (600MW) and caters irrigation to 227.62 Th. ha in severely drought prone Kalahandi district in Odisha has commenced operation from 1999. Two Link Channels is constructed to interlink the Godavari- the Mahanadi basin. The power House tailrace water is diverted for irrigation to 128,000 hectares via Hati barrage. To solve the necessity of electricity and water for irrigation it is necessary to evaluate sediment entry to the reservoir and lifespan of the project in remote inaccessible forests of Dandakaranya Hills.

Present work uses the remote sensing technology to estimate the sediment fill of the Indravati Reservoir. The base map was set taking help of Survey of India Toposheet 65/M/2; 65 N/1, 65I/14, 15, &165; and 65J/9,13 of high precision, georeferenced. Supervised classification and thematic map and DEM (from vector data) has been prepared using Earth resource data analysis system (ERDAS) and other image processing software and analysed. The sediment difference maps of 1996-2001, 2013-2017 and 2017-2021 maps are analysed and compared.

The inference is that the sedimentation in the Indravati reservoir is highest than other sub basins of the Godavari basin. The action for the catchment treatment plan needs study of the anthropogenic strategies which need prioritisation. Upstream Check dams, catchment treatment plans, and vegetation screens along the upstream of the rivers/drains can check the inflow of larger particles from the catchment to the reservoirs.

Keywords: Catchment treatment , GIS/RS, reservoirs, Sedimentation, Renewable energy

Introduction:

Reservoirs are anthropogenic structures across rivers that control and supplement water in crises. India has 5334 large, mostly multipurpose dams constructed with a gross storage capacity of 332361.5 MCum and 411 large dams under pipeline. To regulate the inflow, storage, and spill from the reservoir it is essential to optimise the benefits. Annually a huge quantity of sediments is carried with flow from the river basins based upon the terrain features, land use and land cover (LULC), and anthropogenic interventions to the soil topography add to the sediment/debris inflow to the reservoir, threatening its longevity. To assess the sedimentation rate and the reservoir's longevity, it is indispensable to conduct sedimentation surveys periodically. Efficient management of Hydrographic surveys of reservoirs provides information about sedimentation patterns to control sediment inflow and take remedial measures in advance to plan for the reservoir operation table for floods and irrigation scheduling for optimum water use (Compendium CWC 2020[1]).

The Upper Indravati Hydro Electric Project (UIHEP) is active. The Upper Indravati river valley project (UIP) is a Pumped Storage Hydroelectric Scheme (4X150MW), constructed at Mukhiguda housed in Kalahandi district, Odisha. The irrigation potential of the reservoir is 118041 Ha land in 393 agro-villages during kharif season, while 57,629 Ha gets irrigation, from the right canal, 34,080 Ha from the left canal and by lift canal to 25,846 Ha (NIH 2001[2],RTI data UIP 2017 [3]).

The maintenance of health of the less explored Godavari basin has been attempted by construction of the multipurpose project. The dam has been constructed from 1989. But the sedimentation the reservoir is depleting its water storing capacity which warrants the study about deterioration of its multiple activities for which it is constructed.

Study area:

The Indravati River originates from the western slopes of Eastern Ghats Belt Hills (EGBH) in the Kalahandi district, flows amidst the Dandakaranya areas having catchment (60 watersheds and total catchment of 38306sq. Km.), in the Chhattisgarh and Odisha states from an elevation of 915 m, and finally joins the river, Godavari. (MoJS, 2023[4], Sharma, et al,[5] 2023)

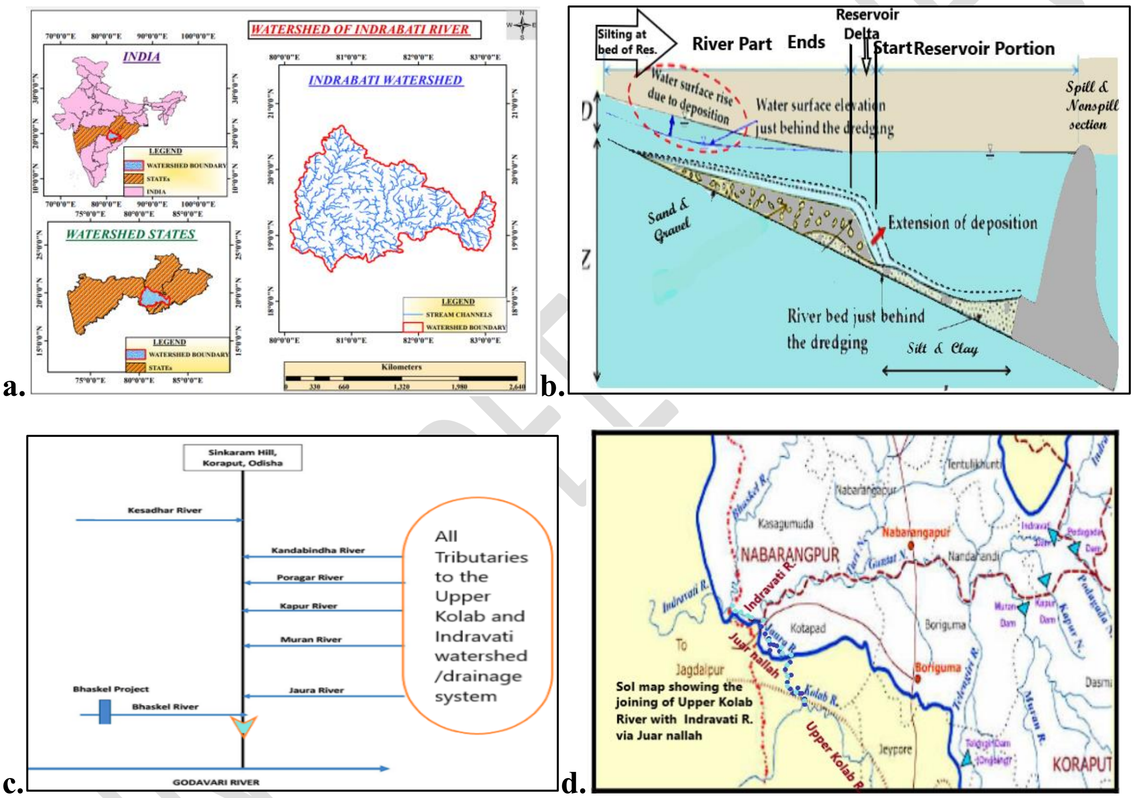


Fig 1: (a) Index map UI Basin (b) Reservoirs Silting (Source: Ahn et al, 2024) (c) The Tributaries of Indravati and Upper Kolab system (d) The interconnective Jaura nallah between Indravati and Upper Kolab R.

The Indravati River originate from the Lamtaguda/Mardiguda villages (Dandakaranya) on the western slopes of Bijipur Hills in Kalahandi District from a height of 915m. Upper Indravati Project, (UIP) is the largest multipurpose projects of Odisha for Power and Irrigation. It is housed in the Kalahandi and Nawarangapur districts. It adds to inter-basin water transfer between the Godavari (Indravati R.) to Mahanadi Basin via a barrage over the Hati River.

The Indravati River passes through 21 dams drains from a basin area of 7435 km^2 in Odisha. The Nallas (drainage channels) joining the Indravati River are Keshadhara, Chandragiri, Kandabindha, Golagar, Podagarh, Bangiri, Parlijori, Chourijori, and Damayanti. Telengiri, Turi, Kora, Modang, Padrikundijori river, Jaura river and Bhaskel river are the major tributaries from the left. Deopalli, the endpoint of the Reservoir. The Indravati has a catchment of 1153Km^2 . The Salient features of the reservoir and the hydraulic structures are in Table 1.

Table 1: Salient Features of Various Hydraulic Structures in the complex but huge UIP, Odisha

Hydrology of the upper Indravati Basin		**Characteristics**	Indravati Dam	**Muran Dam**
Characteristics	Data of 2025	River	Indravati R.	Muran R.
Catchment Area	2630Sq Km.	Length of River	558.96km	
Coordinates of Basin	19° 05'/19°25'N	Place	Khatiguda;	Kalahandi
	82°45'/ 82°55'E	Latitude	19°16'N,	19^0 -60' N
Av. Annual Rainfall	1792mm	Longitude	82°50'E	82^0 - 46' E
Maximum Rainfall (yearly)	2345mm	Operation/ Structure Type	gravity/Masonry	gravity/Masonry
Minimum Rainfall (yearly)	1138mm	Catchment area	1153sq km	1028Sq Km
Probable max Flood (PMF)	23030Cumec	Dam length/ ht. /width	539m/ 45m/7.5m	590.9/65/7.5
RESERVOIR		Dam top Level	495.9m	495.9/m
Full Reservoir level	642m (FRL)	Non-overflow	410m	495.9m
Max Water level (MWL)	643m	Spillway capacity	11430Cumec	8000Cumec
Max Drawdown Level	625m(MDDL)	Overflow section	7spillways/ 129m	95m spheres incl.
Gross Storage Level at FRL	2300MCum	Spillway Crest level	629.5m	645m
Live Storage	1485.5MCum	Radial gate No/Width/Ht	7No./15m/12.5m	5nox15mx12.5m
Dead Storage	814.5MCum	MWL Capacity	11430Cumec	8000cumec
Water Spread Area(FRL)	110 sq km	Depletion Sluices	4Nos	4nos
Inflow at PMF	27070 cum	Width/ height of Sluices	2m x 3m	1.5mx4m
Power House (600MW)	Mukhiguda	Discharge(MWL)	555Cumec	588cumec
Characteristics of all earth-fill dams in UIP				
Characteristics	**Podagada Dam**	**Kapur Dam**	**Other structures**	**Nos/Capacity**
River	Podagada R.	Kapoor Nallah	Dykes	4 left+ 4 in right
Place	Nawarangapur	Kalahandi	Dyke type	Homogeneous Earth fill
Latitude	19°14'N,	19° 06'N,	Crest level/width	646m/ 7m
Longitude	82° 49'E	82° 47'E	Link channels (2)	Gunturkhal Kusumpadar
Type (Homogenous)	Earth fill	Earth fill	**Irrigation**	
Catchment area	389 Sq Km	60 Sq km	GCA	**136.5 Th Ha**
Dam length/height /width	462m/77m/9m	537m/64m/9m	CCA	76.27 Th Ha
Dam top Level	647.0m	646m	UIP	125.08Th Ha
Parapet Height	1.0m	1.0m	Dist. benefited	SW Odisha
Deepest bed Level	570m	582m	Power Generated	4x150=600MW
Protection U/S riprap + Filter	0.6 m r/r. + 0.3 m. Filter	0.6 m.r/r + 0.3 m. Filter	Av annual Energy	1962MU
D/S	Grass turfing	Grass turfing	Generation on	19.04.2001
Diversion/Depletion Tunnel	one no./ dia 6.2m	No Spillway	Hati Barrage flow	**Mahanadi basin**
Sill Level tunnel (MRL)	650Cumec	No Sluice	Irrigation potential	128Th Ha

Source: http://www.ohpcltd.com/Kathiguda/project

The part of Upper Kolab discharge and the Indravati Rivers naturally flow into the Sabari R. through Jaura Nallah (Mishra et al, 2023[7]). The right bank tributaries/Rivers are the Bhaskel, the Nandi Raj (largest), the Narangi, the Nimbra, the Kotri and the Bandia River. Keshadhara Nalla, Kandabindha Nallah, Chandragiri Nalla, Golagar Nalla, Poragarh Nalla, Kapur Nallah, Muran River, Bangiri Nallah, Telengiri Nallah, and Parlijori Nallah. The Jaura Nallah connects the Rivers Upper Kolab and The Upper Indravati and has changed its direction by 180 degrees flowing northerly and feeding the reservoir got the new name *Ulta Jaura Nallah.*

Position of Indravati River in Godavari basin:

The Godavari is ephemeral and the largest river in Peninsular India. The Godavari River (R.) emerges from Triambak hills at elevation 1067 m in the western ghats belts (WGB) near the Nasik district of Maharashtra. The right tributaries of the Godavari R. are the Darna, the Pravara and the Manjra. The left bank tributaries are the Kadwa, the Purna, the Kadam, the Pranhita, the Indravati and the Sabari and charged during SW monsoon period only. The Indravati R. is the major feeder from Odisha to the Godavari is the life line of Chhattisgarh as it caters water for agriculture, domestic and Industrial use in the Bastar region of the state, providing sustenance to communities living along its banks through irrigation, Fig -2 (MoWR 2014[8]).

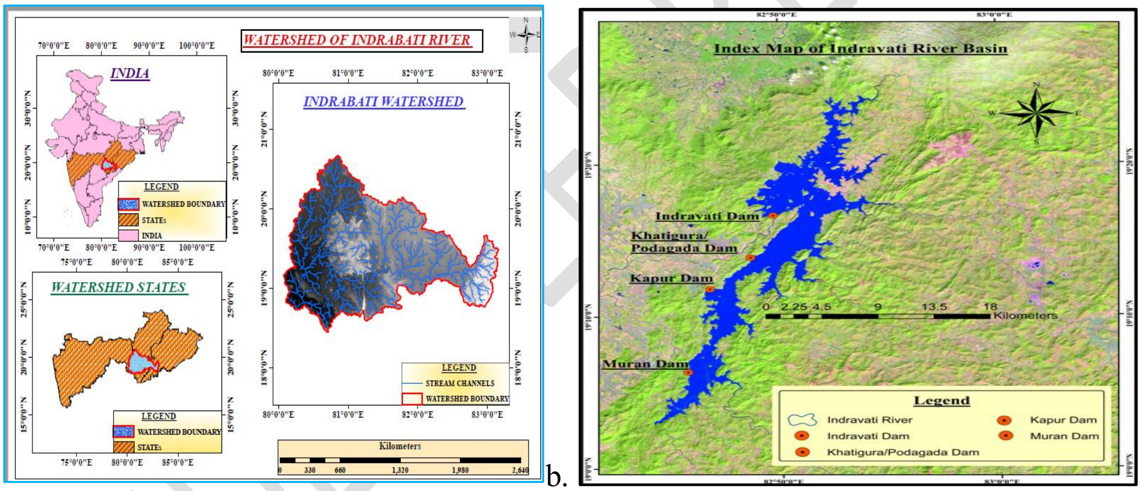
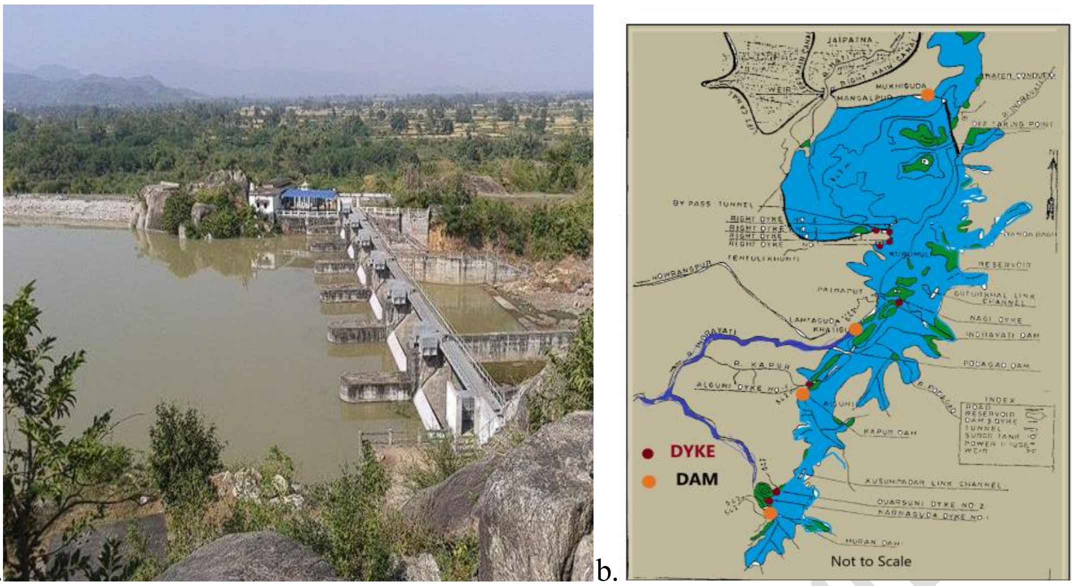
a..  b.

Fig 2. (a) the site map of Indravati River in Odisha(b) Watershed Godavari Basin

The catchment of the reservoir is of exceptionally and unusual terrain, topography and geomorphology and major part is inaccessible. The areas are hilly, undulated and covered by thick vegetations and forest . The area has sparse population, industrially underdeveloped and thin settlements.

Review of Literature:

The GRILSS sediment data tells the highest sedimentation is in Yellow River @ 200 MCum /yr).The dam and its hydraulic structures of UIP is in Fig 3(a & b)(Minocha et al, 2024[9])

a. 

b. 256

Fig 3 (a and b)1: Indravati Dam at Khatiguda (b): detailed Sketch Map Indravati Project

The anthropogenic intervention to land use and Land Cover (LULC) has accelerated terrestrial erosion and sediment transportation deposition in the reservoir constructed behind the dams across river channels, gradually depleting the reservoir capacity along with damming benefits geospatially Mishra et al 2022 [10], Dasgupta et al. 2024[11].

Salal Reservoir along the river Chenab has lost its gross capacity by >95% and a dead reservoir followed by Baira Reservoir in Himachal Pradesh has sedimentation of >81% and the Man Catchment in Madhya Pradesh is 26% , Patil et al, 2021[12], Mishra et al, 2022[13]. Among the east-flowing rivers from the Subarnarekha to the Godavari, the average and median sedimentation rates are 0.76 and 0.68 Th. cum./sq.km/yr respectively, the lowest compared to other zones along the Indian coastal reaches, https://cwc.gov.in/sites /default/files/compendium1122020.

The Mean Annual Rainfall in the catchment area of the upper Indravati is 1423 mm/annually, the drainage density is 3.564m/Km2, and the gradient of the catchment is 0.003. Climate change and anthropogenic stress have transformed strategic energy generation from non-renewable to Renewable Das et al, 2023[14] Fig 2.

Sediment accrued in a reservoir can be calculated by Turbidity meter sediment outflow measurements and water sampling, Side-scan sonar, sub-bottom profiler, and grab sampler, X-ray analysis of sediment cores, Depth surveys before and after the flushing to map the amount and spatial distribution of erosion in the reservoir during a flushing, excavating pits in reservoir deposits, or using a mathematical model and RS methodology as in Balimela Reservoir Jansson et al, 2000[15]. Mishra et al, 2016[16].

Assessment of Different Sustainable Energy Systems, low carbon sequestration, mitigating risk of climate change favouring energy security in India Lawrenz et al, 2018[17], Mishra 2020 [18], Dubey et al, 2023[19], Dash et al, 2024[20]. The renewable potential energy India is in Fig 4.

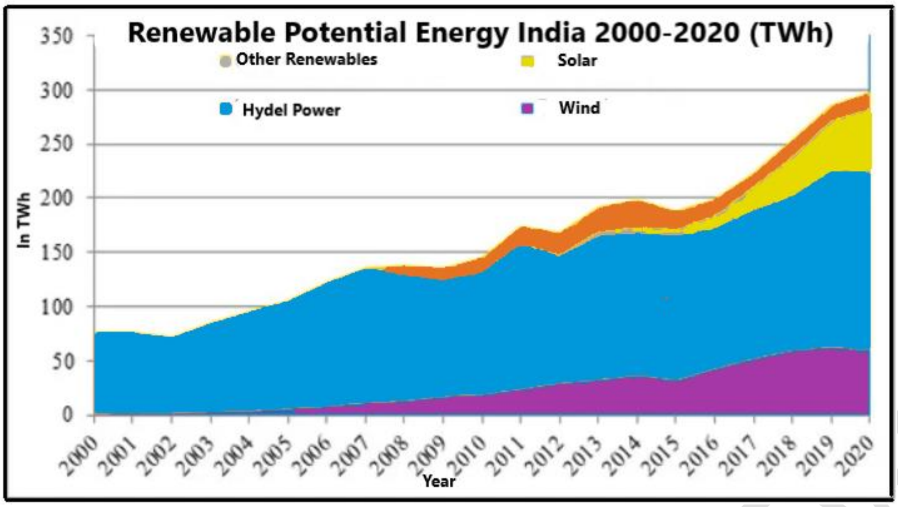


Fig 4. The non-renewable energy generation from 2000 to 2020 in India (source: https://yearbook.enerdata.net/)

The Sediment accumulation rate of the other four major rivers, such as the Mahanadi Basin, Brahmani Basin Upper Kolab, and Balimela Reservoirs on Eastern Ghats Hills, has been calculated using GIS/RS technology. The Hirakud reservoir over the Mahanadi River in Odisha concluded that there has been a 21.44% loss of gross capacity @0.34% / year since impounding from 1957, CWC Compendium 2015[22], Mishra et al, 2023[23]. The reservoir capacity of the Rengali Reservoir was 456.29m3(1990-2000), 402.15m3(2000-2010), and 323.36m3(2010-2020), which is reducing gradually in the last three decades indicating catchment is under regime (Mishra et al., 2022[13]).

Methods and Methodology

Hydrographic survey methodology has been practised for a long time, but it is uneconomic, time-consuming, and requires expertise and experience. Multi-temporal satellite information is used to conduct a capacity estimation survey due to sedimentation in reservoirs which is cost-effective and time-efficient. The methodology helps revise the reservoir capacity table between the uppermost and lowermost draw-down levels observed from downloaded satellite data, which helps estimate the loss of dead storage capacity. The NRSC / DOS/Others are surveying and reporting the National Action Plan (NAP) for 264 reservoirs Table 2

Table 2: Equations used for reservoir sedimentation along the rivers along the Indian Scenario

#	Equation	Abbreviations in equation	When applied	Source
Empirical Formulae				
1	$S = 0.118\,A^{0.815}$	S=Annual sediment deposit rate; A= Catchment area in Km^2	Statistical regression model	The Central Board of Irrg^n & Power (1977)
2	$V_s = 0.0032\,A^{0.72}$	V_s= annual sediment yield in Mm^3	When reservoir data available	Khosala's Equation
3	$ASR=255.4*A^{0.1816}\,S^{0.5774}$	A=basin Area (km^2); S= Initial water storage(ha-m)	ASR =Annual sediment rate(m^3)	Saemaeul Formulae 1970
4	$T_1 = 5.3 + 12.7\,Q\,WA$	Q= annual runoff in M ha m; T is the erosion @MT/ yr., W =T_l/A; A = catchment area(M ha.)	Derived from data from 18 reservoirs	Dhruv Narain arid Ram Babu
5	Qs = 0.59 (A)^(-0.24) where Y = Qs x life of dam	Qs =siltation yearly yield rate (Cum /100 km^2 of catchement);b. Y = Sedimentation Rate (ha.m/	Joglekar Equation	Hatewar et al. 2020

		100 Km^2 / year); A= Catchment area (Km^2)		
6	$Qs = 1.534\,(A)^{-0.264}; Y = Qs\ x\ life\ of\ dam$	Qs =siltation yearly yield rate (Cum /100 km2 of catchement);b. Y = Siltation Rate (ha.m/ 100 Km2 / year);. A= Catchment area (Km2)	Varshny Equation	Hatewar et al. 2020
7	Y = Qs x life of dam where, Qs = 0.323 (A)^(-0.28)	Qs = sedimentation yield rate Annual (m3/ 100Km2 catchement) b. Y = Sedimentation Rate (ham/ 100 Km^2 / year) c. A= siltation area (sq. Km)	Provide lower rate of sedimentation; Khosala's empirical formulae	Hatewar et al. 2020
8	$\Delta V = \frac{\Delta H}{3}(A_1 + A_2 + \sqrt{A_1 * A_2})$	ΔV= change in volume A_1 = the area at contour 1& 2;and ΔH = contour ht. dif. 1 & 2	Prismoidial Formulae; used in RS/GIS formula	Used in present case

Source: NIH Roorkee: 2000-2001[2]

The complex and compound Upper Indravati project (UIP) consists of four dams (Indravati, Podagada, Kapur and Muran), eight dykes (right dyke 1-4, Nagi dyke, Alguni dyke No 1, Duarsuni dyke No 2 and Narnaguda dyke No 1. There are two link channels at Guturkhal and Kusum Padar constructed within the reservoir). The GIS methodology is in Fig 5.

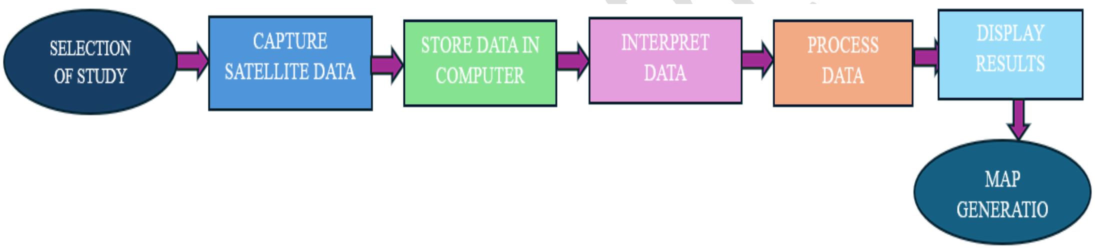


Fig 5: The various steps used for various map generation of Indravati reservoir.

The base map was set taking help of Survey of India Toposheet 65/M/2; 65 N/1, 65I/14, 15, &165; and 65J/9,13 of high precision, georeferenced. Supervised classification and thematic map and DEM (from vector data) has been prepared using Earth resource data analysis system (ERDAS) and other image processing software and analysed.

Geology and Stratigraphy

Anthropogenic climate change is driving spatial vicissitudes in discharges and sediment quantity in east-flowing rivers, which turned out to be a potential domain of research in sedimentology, hydrology and fluvial geomorphology, in thickly populous and ecologically sensitive areas in the EGB Hills zone. The 1000Ma old climate variability and human activities drive long-term changes in river discharge and sediment load, which has become a crucial field of research in fluvial geomorphology, particularly for South Asia's densely populated and environmentally sensitive regions (Haider et al, 2022[24]). Indravati basin. All the dams constructed to achieve optimal economic benefits in their life span across rivers in their mountainous reaches to get a proper George and lean habitation reservoir inundation area. The Upper Indravati reservoir is housed in hilly terrains of Malyavanta Giri of Malkanagiri , Nawarangapur and Kalahandi, districts , covered by forests and thinly populated (Mishra et al, 2023[25]).

Reservoir capacity survey techniques:

The survey of sedimentation of a reservoir can be estimated by orthodox method or modern innovative methods. Otherwise, methods used are hydrographic, topographic and bed material sampling methods. The conventional survey method involves usage of regular survey gadgets and equipment like Total station, theodolite, range finders, compass, GPS, plane table, slow moving boat, sounding rods, Bathymeter, echosounder (depth measurement) etc. The present reservoir survey methodology involves Positioning System (This includes GPS Unit in differential mode), Depth Measuring Units (by using Echo-sounder and Transducers), Computer System: (applying Plotter, Printer, Disc Drive, Monitor etc). Futuristic dam capacity estimations methods are use of Robotic Boat Survey, and GIS/RS applications, and Light Detection and Ranging, (LiDAR), or Air- and UAV-borne etc.

Lifespan of Reservoirs:

The depositional and diagenetic history fixes the life of a reservoir has six periods Table 3.

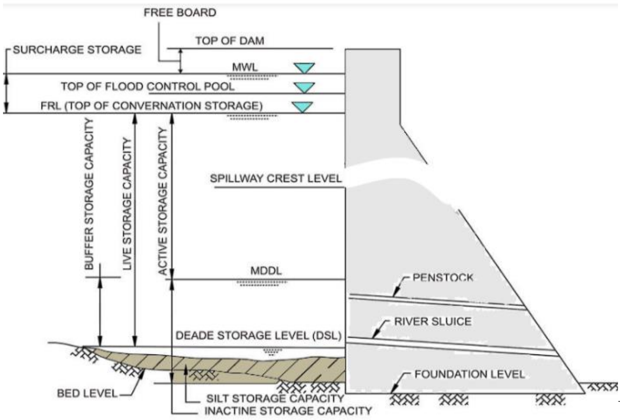
Table 3: Scaling of benefits received from depositional and life span of the reservoirs, India

Periods	Service Time	Benefits delivered	Operation	Effect Hydraulics /life
1st phase	Full-service time	Full-plan benefits	About 100yrs	600MW HE Capacity,
2nd phase	Feasible service Time	Relatively small	Operation continues	Positive Economic effect
3rd phase	Less feasible service time	Relatively very less	Operational difficulties	Sediment Jamming Flow
4th phase	About End of physical life	New zero life to be designed for least benefits	Almost impossible to operate	Reservoir operation plan to be changed
5th phase	Benefit ceases completely	Even after fixing New-zero fixing no benefit	End of economic life	Changed to swamps ; Ave-sanctuary; fish ponds or encroached for farming
Spl. phase	Dam failure	Benefit become zero	$F = 4 * f1 * f2$	Disastrous and deaths and economical loss

Source: CWC Compendium 2019[26], and 2020[1]

Depositional and Diagenetic History

The Indravati Basin, which covers 9000 km2 and flows mainly through Bastar and Dantewada in central Chhattisgarh and south-west Odisha Koraput of Orissa (Fig.1a), represents good outcrops of the Proterozoic Indravati Group of sediments. The composite Lithographic successional formation of the Indravati Basin is the Jagdalpur Dolomite Formation (1200m-250m), Kanger Limestone (150m-200m), Cherakur Sandstone Formation (150m-60m), Tirthagarh Formation (60m - 50m) and the upper-layer is Granite or Supracrustal basement. A.



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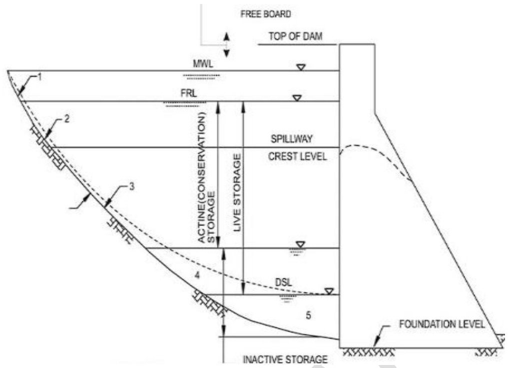
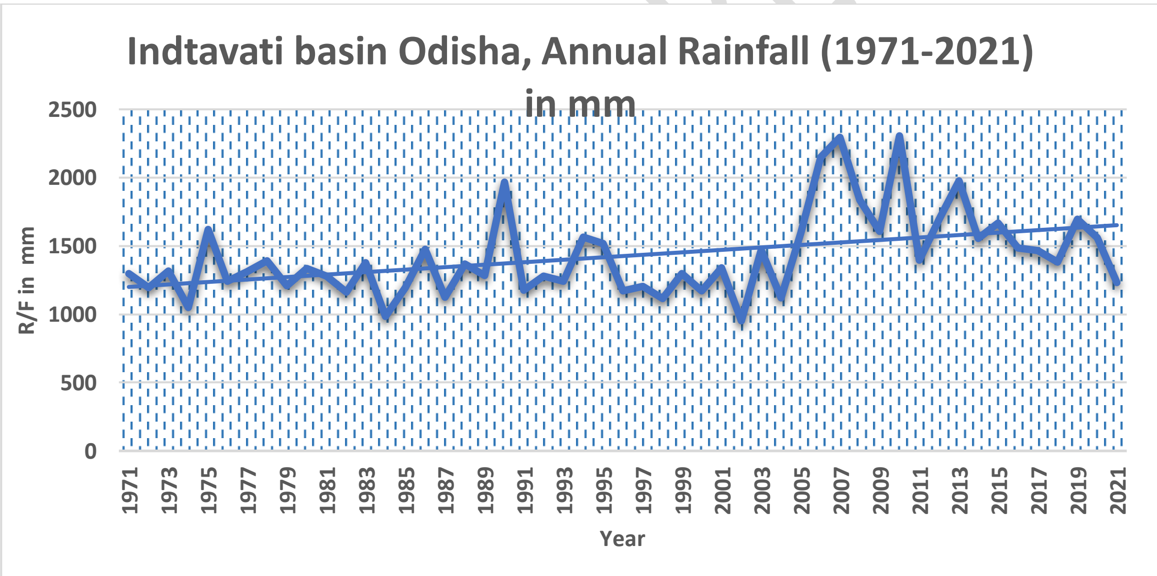


Fig 6 (a and b) Various levels and their uses for the project

Climate:

The maximum and minimum temperature of the appreciably cold area lies between 28^{0}C (summer) and 8^{0}C (winter) respectively but is pleasant. The Relative Humidity (RH) in dry goes below 30% and the wind in summer and winter is Southwest and northwest and west and northwest respectively



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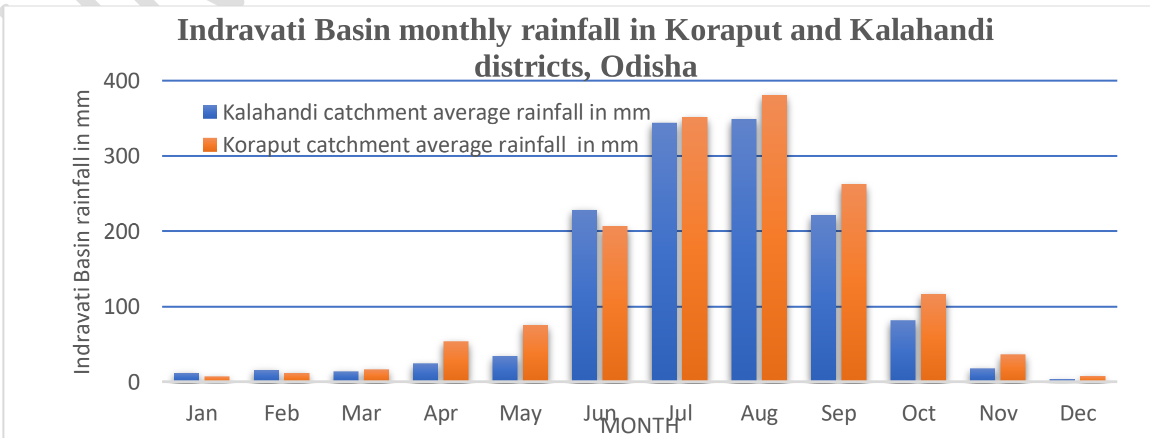

B.

Fig 7: (A) The annual rainfall in the Indravati R. basin in Odish, B) The month-wise rainfall in districts in the Indravati R. Basin.

The reservoir area is housed in EGB Dandakaranya hills range, with tropical monsoon climate with hot summer and cold winter with optimal max of 400C to 100C where the average annual rainfall (R/F) 1431.05mm whereas SW monsoon rainfall is about 1259mm. The same information in the Koraput and the Kalahandi districts comprising the Indravati Basin is 1341.3mm and 1521.8mm respectively when the av. rainy days are 65days/year. The Mean Annual Rainfall in the catchment area of the upper Indravati is 1423 mm/annually, the drainage density is 3.564m/Km2, and the gradient of the catchment is 0.003. Climate change and anthropogenic stress have transformed strategic energy generation from non-renewable to Renewable Das et al, 2023[13].

The Upper Indravati Dam and Reservoir:

The reservoir behind the upper Indravati dam at Khatiguda (Lat: 19.27^0 N and Long: 82.82^{0}E) in Nawarangapur Dist. was impounded in the year 1989 have a minimum drawdown level (MDDL) of 625.00m; Full Reservoir Level (FRL) of 642.00m, Catchment area of 2636`Km^2 (2007 data). The reservoir with Reservoir Area of 110.00 Sq.km at FRL 642.00m. It has av. a trending of NNE-SSW direction. The length of the stripped reservoir is of length 43km and 9km (widest point) and a maximum depth of 71m. The dam project (19°16′34.8″N and 082°49′42.4″E) completed in 1996 of length – 539 m, Height - 45 m, and surface area 110Km^2 opening date – 1999 with designed catchment area 2636Km^2 . Fig 1(b) and Table 5

Table 4: The survey and sediment details of the Upper Indravati Project (UIP), Odisha

Status	Reser-voir	Year	Basin Area	Reservoir Capacity (MCum)			Live storage	Storage Loss	% Loss last survey
			Sqkm	Gross	Live	Dead	MCM	MCM	%
Impounding	UIP	1989	2636	2307.71	1455.77	851.94	1455.77	0	0
Survey Year	UIP	2007	2636	2307.71	1455.77	851.94	1483.91	-28.14	-1.93

Source: Compendium CWC 2020[1]; Source: WS&RS Directorate, EMO, CWC; India

Upper Indravati Hydro-Electric project

The multipurpose UI Hydroelectric Project (UIHEP) is a part of UIP and is at (lat of 18° 45' and 19° 40'N and long. of 82° 43' and 83° 10'E with a catchment area of 2636 sq. Km.(SoI TOPO sheet Number 65 M/2 to 4, 65 I/14 to16, 65Jl/9 &13 and 65 N/1. The maximum depth of the reservoir is 71 m. and an av. depth of 21 m is transported to the Power House up to Mukhiguda in Kalahandi district by a Headrace channel of 335 m long and 3934 m long, 7 m diameter (Ø) circular tunnel ended at surge shaft 52cm Ø 140 m deep, 2 nos 298 m long 5.25 mØ Penstock tunnels and 4 nos 790 m long 3.5 m Ø surface penstocks. The Powerhouse (PH) comprises four units @150 MW installation at a 371m average head to generate 600 MW and annual hydel power generation 1962 MU at a 90% dependability. The water from the draft tube of the PH is conveyed by the 9000 m long tailrace channel and debouched at the barrage over the Hati R. and cater irrigation to 128000 Ha to the regular drought-affected Kalahandi in the Mahanadi Basin.

GIS Studies

Aspect Map: Using DEM data an aspect map gives a 3-D visualisation that exhibits the direction and steepness of a landscape's slope. It shows the valleys and ridges that are prone to fire and landslide, and the impact of fall of solar radiation. The aspect map that decides the erosion and moisture of soil , the weathering processes, and vegetation etc. of Indravati basin for 996, 2002, 2013, 2017, 2021 and 2024 Bouzekraoui et al, 2024[27] is in Fig 4 (a to f).

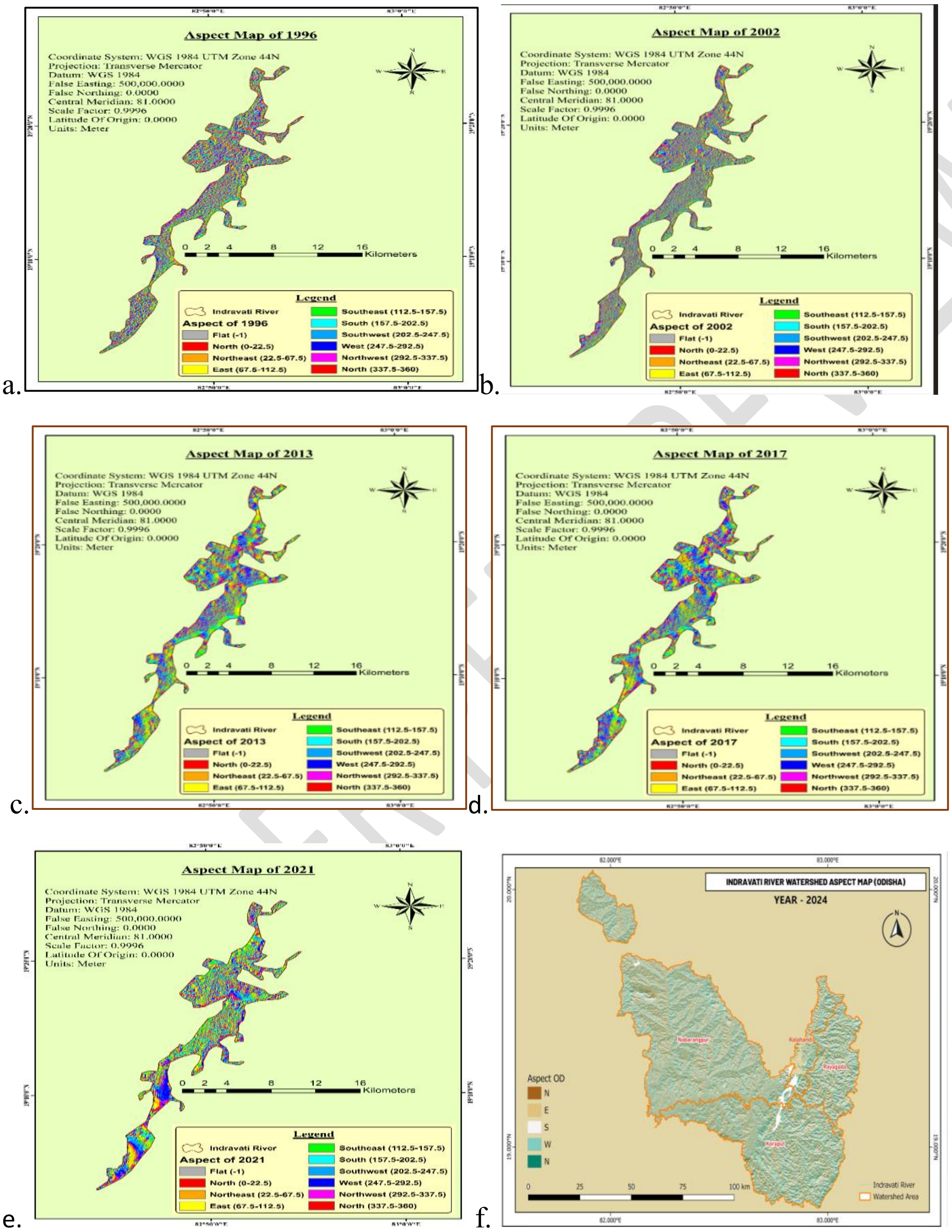

Fig 8 (a to f): The aspect Map of the watershed of UIP 1996, 2002, 2013, 2017, 2021 and 2024

Slope map: In Arc GIS Pro, the slope map is a tailored vision of a terrain's steepness. It is generated using tools from DEM contours, such as the Topo map or the Raster and Slope tools to assess to determine the hydrology, morphology, sedimentology, and ecological state of a mountain watercourse Ajaaj et al., 2024[28], Cislaghi et al, 2024[29].

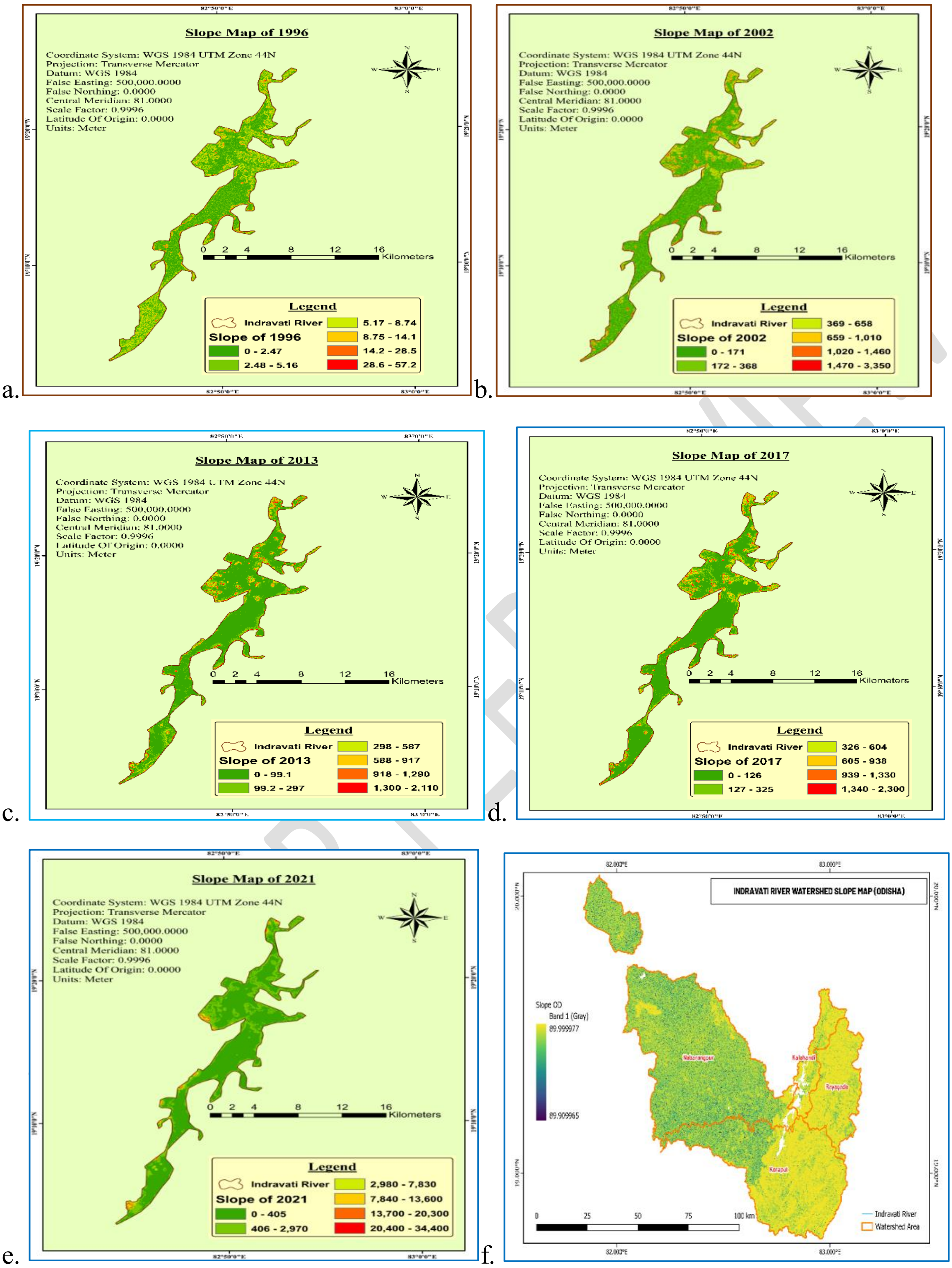

Fig 9 (a to f): The slope Map of the watershed of UIP 1996, 2002, 2013, 2017, 2021 and 2024

Sediment difference map:

By using the sediment difference map one can assess the variation in sediment buildup within a reservoir over time, (increased or decreased) from bathymetry data of the waterbody in a basin. The analysis methods are overlaying data and difference in elevation of layers. These maps are used for reservoir management, Environmental monitoring, or WR planning. The sediment difference maps between 1996-2002, 2013-17, and 2017-2021 that report Sediment Yield and finally computation of Reservoir Sedimentation Ayele et al, 2024[30], is given below(Fig a to d)

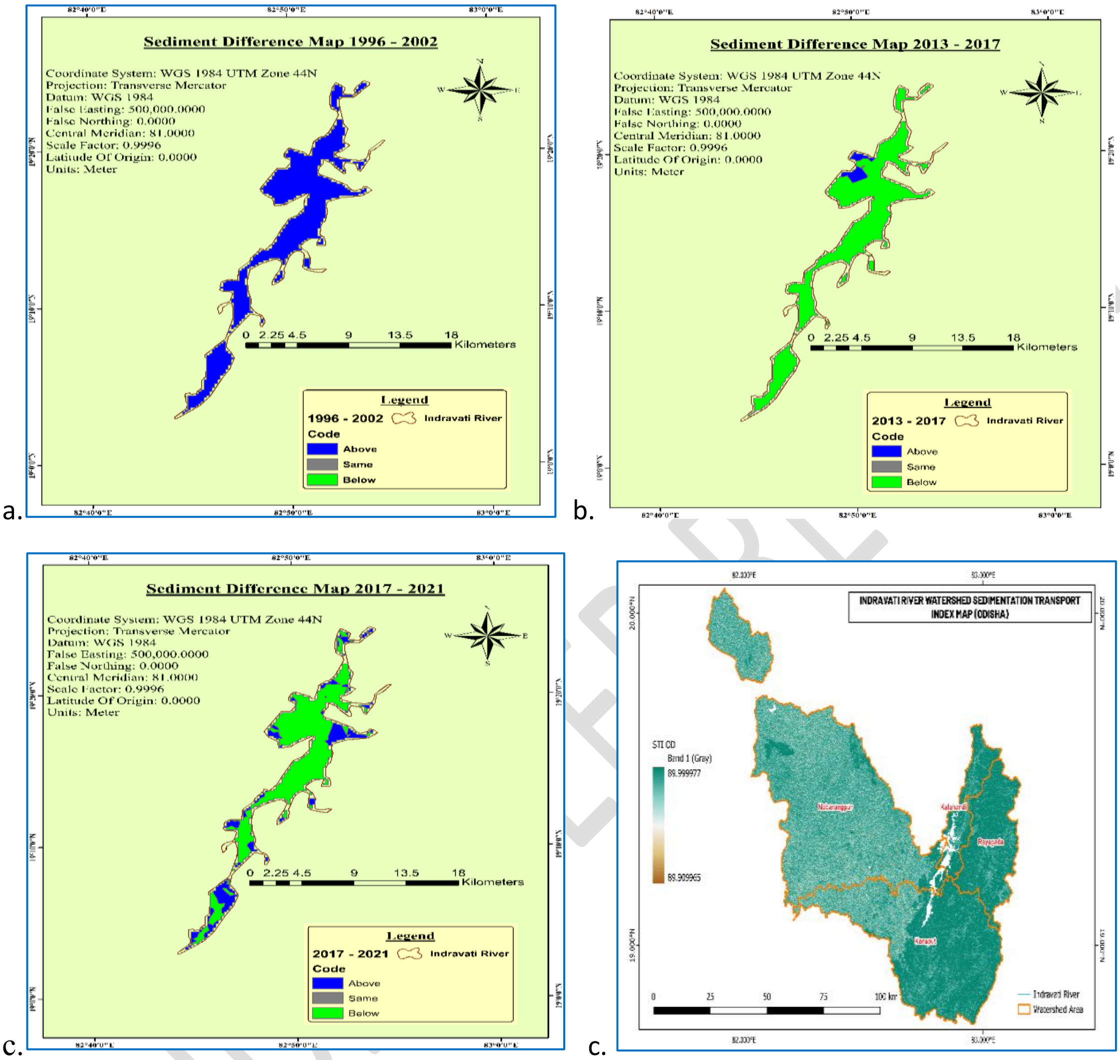

Fig 10 (a to d): The SDI Map of the watershed of UIP 1996, 2002, 2013, 2017, 2021 &2024

Contour Map of Indravati Basin

The isohyets lines (Contours) depict the position of periodical changes due to sedimentation in the bed of a reservoir Ahn et al, 2024[31]. https://krishi.icar.gov.in/jspui/bitstream/ 123456789/ 18498/1/Machiwal_et_al_rev_Krishi_Portal.pdf[32].

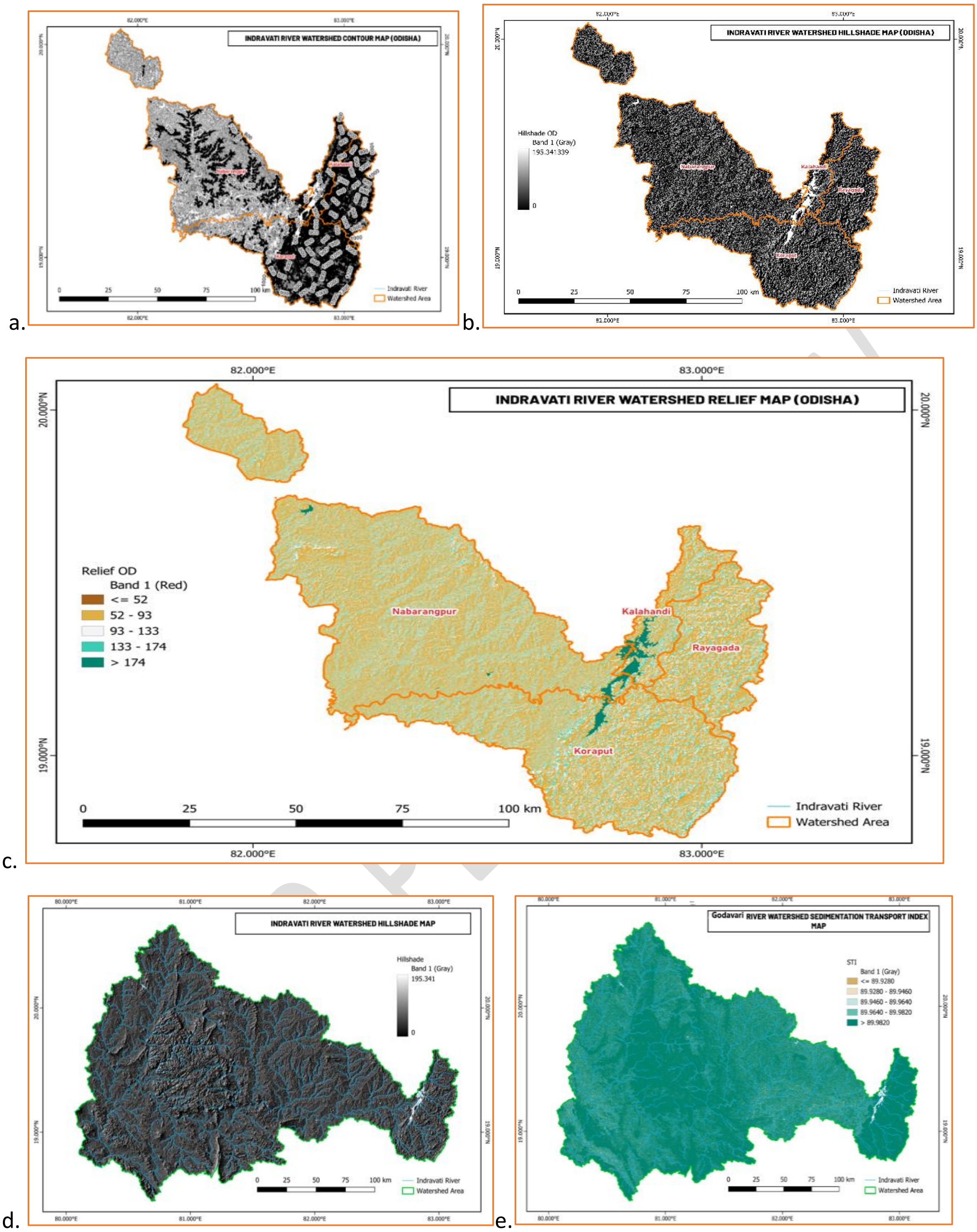

Fig 11 (a to d): (a)The contour Map (b) the watershed map; (c) Watershed Relief map (d) Water shade and Hill shade map; (e) Watershed sediment transport Index of the watershed of UIP in Godavari basin 2024

The water shade and Hill shade map of Indravati project infer about closeness of drains and the area is in Dandka-Aranya hills of mid-eastern ghats belt of Odisha as the contour lines are very close to each other.

Sedimentation in the Basin:

The RS technique provides synoptical, repetitive, and judicious information about a reservoir's geodetic surface area and has the advantages of geospatial, spectral and temporal, attributes. water body. These applications can calculate spatial patterns of sediment /silt determination

The volume of sedimentation or scouring of a reservoir can be calculated by the prismoid formula taking elevation between two consecutive elevations (ΔV) of the reservoir, the reservoir capacity(ΔV) can be computed using the prismoidal formula:

$$\Delta V = \frac{\Delta H}{3}(A_1 + A_2 + \sqrt{A_1} * A_2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where at two consecutive elevations (1 and 2); A_1 = the area at contour 1; A_2 = the area at contour 2 and ΔH = the difference between contour 1 and 2

Table 5 (a): The evaluation of annual sedimentation of Indravati reservoir in various years.

Years	Volume	Calculated Catchment Area	Total Siltation
	MCM	(km²)	(MCM)
1996-2002	2399.56	2754.36	2546.66
2013-2017	2218.31	2544.82	198.13
2017-2021	2278.19	2686.08	274.91
Reference data			
1989.00	2307.00	2636.00	NIL
Error calculation			
1996-2002	4.01	4.49	NIL
2013-2017	3.84	3.45	NIL

Calculated Catchment Area (km²)	Total Siltation (MCM)	Total Scouring (MCM)	Water Spread Area (Km²)
2636.00	NIL	NIL	110.00

Catchment Area (%)	Siltation (%)	Scouring (%)	Water Spread Area (Km²)
4.49	NIL	NIL	21.52
3.45	NIL	NIL	18.66
1.89	NIL	NIL	21.40

. The original volume and revised volume are compared in each zone. It is gained from the original elevation–capacity table. The difference causes volume loss due to sedimentation. The contours are used to make a DEM of the area and data from two dates give the depth of sediment accruing or scouring at many points. The RS approach is economical, user-friendly, in-accessible reservoirs and time-efficient compared to orthodox methods.

Table 5 (b): The annual sedimentation, scouring, % of volume change of Indravati reservoir

Years	Volume	Calculated Catchment Area	Total Siltation	Total Scouring	Water Spread Area	Volume	Catchment Area	Silting	Scouring	Water Spread Area

	MCM	(km²)	(MCM)	(MCM)	(Km²)	(%)	(%)	(%)	(%)	(Km²)
1996-2002	2399.56	2754.36	2546.66	207.7	86.32	4.012	4.49	NIL	NIL	21.52
2013-2017	2218.31	2544.82	198.13	2346.69	89.47	3.84	3.45	NIL	NIL	18.66
2017-2021	2278.19	2686.08	274.91	2411.17	86.46	1.24	1.89	NIL	NIL	21.4

The drawbacks of the RS methodology for estimating sediment accruing at the debris/mud-laden lowest surface cannot be marked accurately leading to wrong estimation of sediment rate. Clouding over the lacustrine area poses the problem of demarcation between land and water bodies. If the lacustrine area of a reservoir is along a narrow strip side valley, the surface area of the water bodies has a minimum change in the water levels, then remote sensing methodology for sediment calculation is inaccurate (Jain et al, 2011[34]).

Discussion:

Sediment is carried from the catchment to the reservoir through the inflowing rivers. Deposit along the longitudinal section is in gradation from boulders to silt and clay at the bottom of the gravity-type masonry dam whose design longevity is about 100years. The dead storage is 851.94 MCum. The deepest bed is at level 600 meters. The dam is fixed at level of minimum drawdown is 625 m and gross/live storage 2307.70 MCum 1455.76 MCum respectively. No new zero level is fixed by Jan 2025. The catchment of the river Indravati lies in the Godavari basin the average rate of sedimentation should be about 2.27Th.cu.m./sq.km/yr but the observed sedimentation calculated is higher which is 3.03Th.cu.m./sq.km/yr , CWC Compedium 2020[1], Perrera et al, 2023[35].

The GIS study of the catchment areas of the reservoir reported by the National Institute of Hydrology that the scrubland, total Forest area and arable land comprise 59%, 11% and 21% respectively. The scrub lands and arable lands have 3.61% and 0.9% respectively. In contrast, other overall land categories like settlement, water bodies, and forest lands have increased by 3.77% with annual sediment yield oof 2.75 to 4.282 Cum/Ha/Year between 1996 to 2000.

It is reported in The New Indian Express on July 9th 2018 that due to acute sedimentation in Indravati Reservoir, accumulation of silt was found to be more than 3m before entry to intake wale that was hindering irrigation, power generation potential and water supply. It is pertinent that all reservoirs in India are suffering from sedimentation depending upon the shape, size, topography of the basin, slope/soil of the catchment, and rainfall pattern. Anthropogenic interventions such as land use and land cover (LULC), forest, vegetation, and intervention to the catchment.

Innovative solutions

The management of reservoir sedimentation is being done by various methods done in India. The popular methodology is by dredging the drains debouching the Indravati reservoir which is costly and time consuming, but a temporary measure. The 2nd practice employed are Sediment flushing by silt extruder or silt extractors constructed during dam construction. The alternate can be thought of by construction of bypass (or diversion) that diverts the flow downstream via a separate channel, and can minimize the sediment entry to the reservoir during peak flow events that reduces and efficiency achieved 80%–90% with well-judged Operation and Maintenance Manual as per Dam Safety Act, 2021, The Dam Safety Act, 2021, NO. 41 OF 2021, [13th December, 2021.Perrera et al, 2023[35],

Other strategies that can ameliorate the problem of reservoir sedimentation are by reducing sediment yield by either sediment trapping, erosion control in the upstream (U/S), dealing high sediment inflow to minimize trapping or already trapped sediments, other benefiting structural or functional methods. Other method can be adopted to increase the dam height to augment reservoir capacity or increased impounding area. Demolishing dam shall reorient the old statuesque of the river or to fix a new zero level for the dam Shrestha et al, 2022[36].

Estimating reservoirs is a state/central government task. As the benefits received from the dams and reservoirs add to the national economy, the users and stakeholders become careless about preserving the new ecosystem that flourished after the impounding. The Government is also not paying any attention to the systematic study of the development of the novice ecosystem of flora, Fauna, avifauna, and aquafauna.

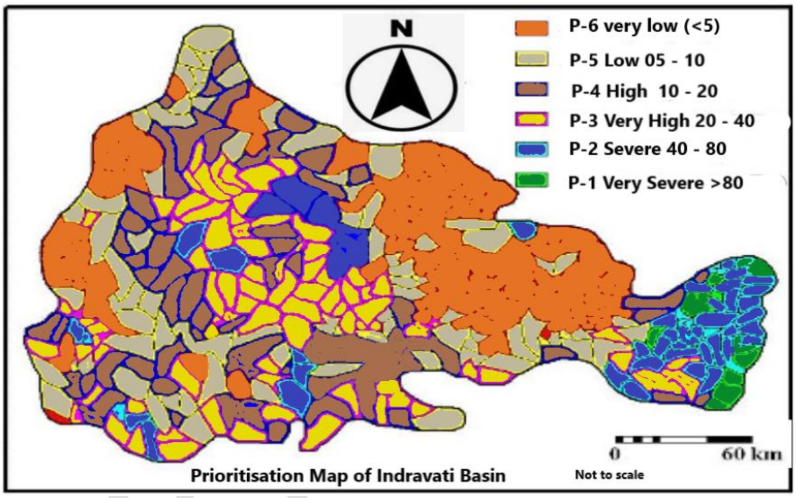

Fig 12: Prioritisation map of the watershed management of Indravati Sub-basin (Source: Vemu et al, 2012[37])

From the prioritisation map it is evident that the upper Indravati Sub-basin and the lower Indravati basin are prone to sever and very severe scouring. The high rate of sediment entry from the catchment to reservoir shall accrue and accelerate the sedimentation process of the Indravati Reservoir early for which pertinent catchment treatment process is warranted.

Sedimentation Impacts:

Reservoir depletion by sedimentation distresses various benefits of reservoirs, the water stresses with anthropogenic interventions in the basin with population projection in the coming decades (Lee et al, 2022). The negative impacts of sedimentation are (i) Lessening of storage volume (ii) increase in flood level in Upstream of reservoirs (iii) Risk for bank erosion and bed incision at D/S (iv) Risky operational strategies for flood control dams, (v) adverse impact on crop yield (v)Sinking shrinking and subsidence of deltas (vi) augmenting coastal erosion near estuaries (vii) Impact on flora and fauna (viii) Stress on coastal and (ix)Reduction in infiltration rates and increase in tillage operation. Though 21numbers of dams re in operation in the basin but it is very less to check the sediments entry to the basin (CWC data).

Conflicts interstate: The possible skirmishes for a dam-based reservoir are conflicts of space time and discharge**.** The Jaura Nallah (tributaries to the rivers Kolab and the Sabari) that carries surplus water of the Indravati River lies at the D/S of the Upper Indravathi Dam, having catchment area of ≈4800sqkm in the Indravathi Sub-basin lies on the Chhattisgarh, Andhra Pradesh and Orissa border. Presently Odisha state demands water of the Indravati sub-basin to utilise in its most drought prone areas of Indravati, Nawarangapur and Kalahandi districts. It is the major interstate conflict on water issues demanding a flow of ≈45 T.M.C till unsettled (Mishra Manoj. 2016[38], Dahe et al, 2018[39]).

Sediment entry Remedies

All dams are Unique and have diverse sedimentation process that affect its benefit in longrun due to storage potential loss. Soil erosion strategies and transportation to the back of dam can be catered by watershed management plans and sediment management techniques are(Fig 7):

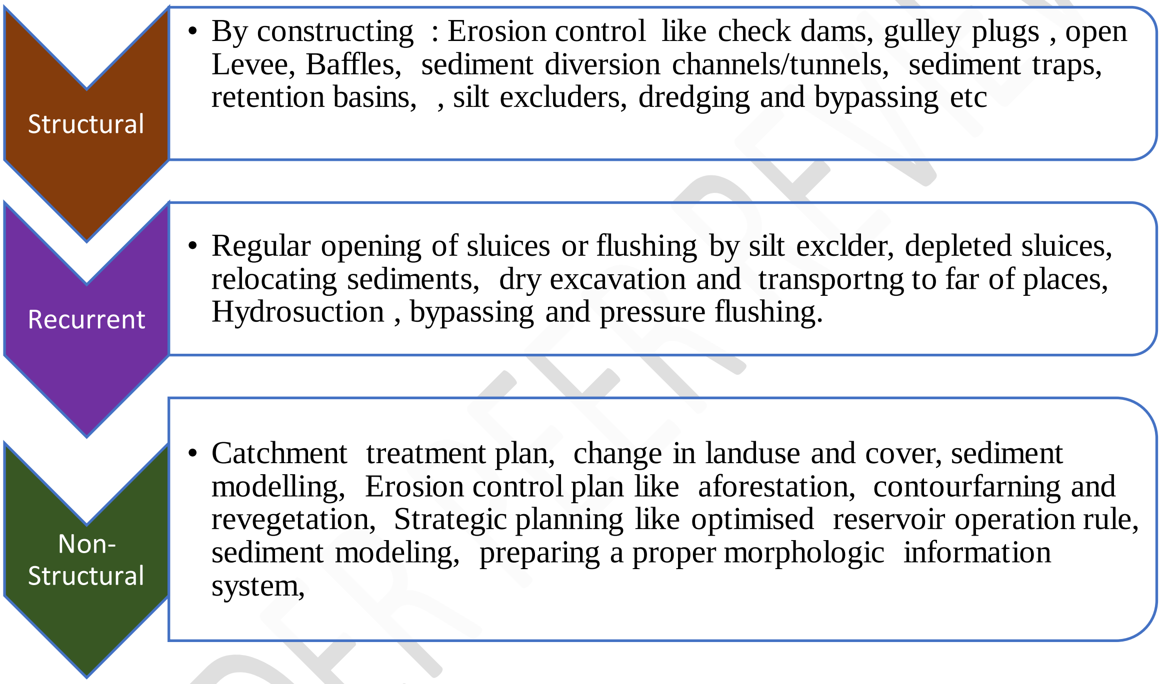

Fig 13: Standard Strategic control, stable slope, erosion and sediment reduction in reservoirs

The sediment management plan of the reservoir involve standard sediment management techniques in reservoirs can be controlled by mainly barring sediment from upstream, Routing sediment by adopting proper reservoir operation rules and removal/redistribution of accrued sediment with adoptive strategies Lee et al 2022[39].

a. The reduction of sediment entry by innovative technique: It can be done by upstream sediment trapping and reducing sediment generation along hillslope by afforestation, revegetation with indigenous plants, farm ponds, gulley/drain stabilisation or check dams in inflowing drains .
b. Sediment bypassing involves sediment bypass tunnels/ channels, high/low level bypassing, seasonal gate operation, under sluice operations etc.
c. Proper reservoir operation rules and removal/redistribution of accrued sediment by mechanical dry excavation and agitated dredging, and removal or relocating, hydro

suction or hydraulic dredging, modifying time of reservoir level for adequate sediment exclusion.

d. The efficient adoptive measures are modifying intakes, relocating storage, increasing storage volume by raising dam heights, storage loss control by regular and proper monitoring conservation and maintaining proper morphologic information system.

The catchment area of the Indravati basin needs catchment treatment activities like reserving forests, restoring vegetation, contour farming, creating awareness about distracting benefits due to sedimentation, sluicing , flushing, sediment diversion structures (bypass or tunnels or channels), weirs, dykes or slope protection works based on present site conditions and human interventions.

Conclusion: It is difficult to capture all in-depth technical aspects, associated with sediment-induced problems of a reservoir behind a dam. Present study envisages the salient features of an active complex and giant hydrodynamic congregation of hydraulic structures of all sorts of one of the largest dams in SE-Asia. All the dams in Odisha are encountering sedimentation problems and reducing benefits gradually and ultimately may make the Indravati dam defunct. Changes in LU and LC by anthropogenic infrastructural developments, mining activities, deforestation, urbanisation and industrial development augments the sediment entry to the reservoir.

Investigation to entry of sediments to abate paucity of data for better planning warrant homework at regular intervals which may be beneficial and useful to increase possibilities of reduction in sediment entry to the Indravati reservoir and assess life span of the project without less loss to its benefits.

Inferences: **i.** Upper Indravati Project (UIP) is one of the largest multipurpose projects in mid-Eastern Ghats belt Hills in mythological Dandakaranya forests.

ii. The Indravati Subbasin in the Godavari Basin largest peninsular India is housed in the Hills and sparsely habitats backward areas have less R&R cost.

iii. The outflow through tailrace of PH and Hati Barrage promoted inter basin transfer between the Godavari-the Mahanadi Basin.

iv. Prioritisation of sediment erosion is maximum in the Godavari basin.

v. The average rate of sedimentation in the Godavari basin as per CWC is 2.27Th.cu.m./sq.km/yr but the observed sedimentation calculated is higher which is 3.03Th.cu.m./sq.km/yr , that may reduce the the design life span.

Further studies: It is essential to include various parameters to estimate the capacity of reservoir like the uppermost and lowermost draw-down levels observed from downloaded satellite data, which helps to estimate the loss of dead storage capacity. The new operational schedule for the complex Indravati reservoir along with other contributing criterions can be framed for the coming years.

The other studies should include formulating plans for managing the impacts caused by Anthropogenic activities and future plan for the downstream water uses. The study should extend to other indicators besides sediment, such as the water flowing into the reservoir, nutrients or chemicals contaminants, for a complete study.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Acknowledged: The authors are highly obliged to, Dr. Deepak Ku. Sahu, Mr Chandan Kumar, Mr. S K Barik and Mr S Manna who contributed a lot in GIS map making during preparation of the manuscript.

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