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Geospatial Sedimentation of Hirakud Reservoir, Odisha

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Abstract

Hirakud reservoir impounded since 1957, across the Mahanadi River, Odisha, India. The River 851 km long has discharged a maximum 44.78Kcumec of the floods that inundated downstream areas, and 9500km2 of its delta region. The Hirakud reservoir commands assured irrigation to 2669 km2 and hydropower installations of a capacity of 347.5 MW of Odisha. But the dam traps about 79% of sediment received from upstream. Sedimentation, basin mismanagement, and numerous hydraulic structures have deteriorated the morphology and sediment status of the reservoir. Web-based GIS, LANDSAT, and Multi-date RS data in the web platform help in building various digital maps for meeting utilities. Present studies have utilized SRTM data for index and stream order maps and different LANDSAT data for achieving stream order, contour, aspect, and water spread area maps to quantify sedimentation in the Hirakud reservoir. Continuous sedimentation of the Hirakud reservoir has lost its 34% live storage capacity since 1957, causing the delta to sink, shrink, and subside. The diminution of storage, erratic basin rainfall, and occasional high floods caused by dams upstream have warranted fixing new zero level, and reallocation of revised storage for future capacity building. The sediment accrued within the reservoir bed if not cleared, the reservoir capacity and its benefits shall diminish. The basin managers should outwit further sedimentation by e-flow assessment and database preparations by confirming to EIA recommendations/ clearance process.

Keywords: *Aspect/slope map, Hirakud, GIS/RS, Mahanadi Basin, Sediment, Area-elevation*

Introduction

Damming the rivers decreases flow velocities, and enhances sedimentation, resulting in larger materials deposited at the tail end, finer clay, and silt near the dam's toe. Sediment may clog vents of excluders and turbines disrupting dam activities [1], [2]. Hirakud reservoir was first impounded in 1957, behind the longest composite dam across the Mahanadi River, in Odisha, India. Continuous sedimentation, unplanned basin mismanagement, and many hydro logic interventions upstream are the deterioration in the morphology and biochemistry of the reservoir. The sediment accompanying flood flow has generated 9500km2 of the highly fertile delta. But the dams have trapped about 79% of sediment with 40% curbing of distributaries, curtailing the reservoir's capacity, and life span, expurgating the targeted human services, and forcing the deltas to sink, shrink and subside [3], [4] (Figure 1).

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The web-platform like GIS/ RS (Geographical Information System and Remote sensing), and big data management with innovative soft computing methods appear as influential gears in investigating geo-spatial vicissitudes of natural resources and help in planning their management. The GIS/ RS techniques are remote; cover a wide-ranging extent, and are non-destructive, real-time, and authentic. Quantifying the deposition of sediment, using satellite data by knowledge of water spread area and capacities at different elevations in the different periods considered to access sedimentation of Hirakud reservoir rather than old survey and robotic methods. The emerging unmanned aerial

Figure 1: Index, DEM, map of Mahanadi Basin and Hirakud Reservoir (Data: SRTM)

vehicle (UAVs) and drones have made the task easier to receive data, and information for spatial analysis, and visually represent the nonvisible signals of near-infrared, thermal-infrared, and hyperspectral bands of various wavelengths. Multi-date RS data in space platform used in getting Hirakud reservoirs elevation contours, and water spread area through DEM (Digital elevation model). The difference between the water spread areas at identified gauged elevations that can indicate the deposit of sediment during that period [1] [5] [6].

Review of Literature

The dams constructed for human services in river basins are enhancing the retention and deposition of sediments in its reservoirs. About 45000 reservoirs (> 15 m dams) trap ≈75% of sediment discharged from their upper basins behind the dams, [07], [08], [09]. Construction of dams and continuous sedimentation of reservoirs behind are regular natural/anthropogenic stresses on the fluvial system around the globe, [10], [11], [12], [13], [14] and [15]. The dam is creating a paucity of sediment load that is making the deltas shrink, sink, and subside globally abetted by regional sea level rise [17], [18].

The Hirakud reservoir shall end its activity by the year 2150 if the sedimentation continues uninterrupted,([1]). The water spread area at FRL was estimated as 743km2 and the corresponding live storage 6151.30Mcum. Under zero dead storage, the capacity was 1953.7Mcum in 1957 whereas in 1989 with annual sedimentation rate was @61.5Mcum, [18]. Change detection of attributes is anthropogenic activities, inflow sedimentology, drain geomorphology, and ecosystem [19].

The sedimentation status study by GIS/ Remote Sensing method of some reservoirs (India) has become popular and adopted by many researchers. Jain SK. [20] studied the capacity of Bhakra Reservoir, Bilaspur, H.P from 1965 to 1996 (32years) has reduced from 9867.84Km2 to 7938.48Km2 with an average yearly loss @9.23% (25.23 Mm3/ yr). Tiwari S. [21]have reported that Teri Reservoir, Uttarakhand, has lost 1.56% of its capacity from 3540 (42m) to 3116.39 (40.11m), @ 11.02 Mm3/yr from 2007 to 2011 within 5years. Pandey, A.. [12] have analysed the silting of the Patratu Reservoir, Ranchi, Jharkhand from 1968 to 2012 (44years) has lost its capacity 101.95 Hm3 to 89.96 Hm3 (11.76%) in 44yrs. Mishra SP.[22] mentioned that the Bramhani River (1993-2012) has an average sediment flow was 5.23MMT and the average flow has raised to 5.957MMT when considered for the period 1993-2014. The sedimentation of Bhopal Lake (2014 to 2017), Vaigaireservoir, Tamil Nadu over Periyar River, Rihand Reservoir (UP), and Ujjain Reservoirin Maharashtra have reduced their live storage capacities by 25.47%, 16.512%, 10.73% and 11.23% during the periods 1958 -1983 (44yrs), 1962 – 2019(58yrs), and 1980 -2021 (41yrs) respectively, [23], [24] , [25], [26]. There are significant downward sediment transmission trends in an influx into reservoirs found in peninsular river basins, [27]. The total capacity of storage, the Hirakud reservoir was estimated to be 6151.30 MCum during 1989 with a capacity loss of 1953.70 MCum (24.10%) with an annual rate of siltation @ 61.05 MCum/annum, since inception [28]. The six major dams and other barrages up-stream of Hirakud dam are retaining 74% of sediment and the annual average discharge of river Mahanadi is about 49.3Bcum/yr carrying an average 11.8 MMT/ yr of sediment from an area of 124 Th. Km2 (2000 to 2010), [29], [30]. Depletion of sediment loading of about 79% occurred between (1973 to1983) and (2007-2017) at Tikarpara, near the delta head as per MOWR. The Hirakud reservoir reported a gradual reduction of the gross storage capacity, longitudinal slope, and changing contour profile due to sediment deposition and the Hirakud dam section is safe for all possible load combinations and needs no further retrofitting at present, [31], [13].

Satellite Remote Sensing (SRS) is a focused branch of GIS having tremendous application in the water resources segment in India for its expansion, and proficient resources management [32], [27], [33]. GIS provides multi-period data, which enables to utilize the multispectral images of the water spread area along with remotely sensed elevation contours (DEM models) to assess the sedimentation and the capacity activities of the reservoirs.

Objective of study

The sedimentation is measured by hydrographic methods, using modern technologies like eco-sounders, robotic boat surveys, or transducers. They are time-consuming, expensive, and liable to the inclusion of errors. GIS and remote sensing methodologies have made the process easy, time-saving, cost-effective, and with an approximate error leeway. The present work is a spatial analysis of the sedimentation of Hirakud Reservoir, especially focusing on the amount of scouring vs siltation that has occurred over the last 3 decades i.e., considering observation years 1990, 2000, 2010, 2013, 2017, 2020, and 2021.

Mahanadi River Basin

The peninsular Mahanadi River basin (MRB) is suitable for hydraulic structures as there is better compatibility between the saucer-shaped catchment decanting to a well-built, ideal arcuate-shaped delta to cater to the demand and supply of various utility sectors. (Figure -1).In the upper drainage canopy of Upper Mahanadi Basin (UMB)of the MRB, mainly houses in Chhattisgarh (87% of the catchment of UMB in 15districts) and Odisha states (13% of UMB, in 2districts Jharsuguda, and Sundergarh). Periodic floods and droughts are common in MRB. Six major reservoirs in MRB are Tandula (1923), Hirakud (1957), Dudhwah (1965), Ravishankar Sagar (1979), Hasdeo-Bango(1990), and Lower Indravati (2012). Hirakud reservoir was constructed aiming to alleviate the problems of flood/drought, hydropower, and urban supplies but the industrial water supply was later warranted. The average annual surface flows at delta head Naraj is66.880 BCM out of which 50 BCM is utilizable, [34], [35].

The states Odisha and Chhattisgarh have problems with water allocation with ogling rapid urbanization, industrialization, and mining exploration. Several dams were constructed in the Hirakud basin. Extreme rainfall cause unwanted reservoirs to spill and overstress the footing of Hirakudreservoir resulting in high floods in the Lower Mahanadi Basin (LMB). Such unwanted floods in 1982, 2008, 2010, and 2014 caused heavy pecuniary losses in Odisha. The sharing state Chhattisgarh in UMB has planned to utilize water through "ongoing", "pipeline" and "future" projects is about 23646Mm3, which is greater than the annual average runoff of 19242Mm3 of the river. The continuous sedimentation of the Hirakud reservoir has depleted its live storage, and gradually lost flood absorbing capacity that warrants continuous monitoring of LMB, [36].

Study Area

The basin: The 851km long Mahanadi River is an east-flowing, saucer-shaped canopy of an area of 141672 km2, (4.3% of India's landmass). The basin houses in five states, Maharashtra (0.07%), Chhattisgarh (53.07%), Madhya Pradesh (0.1%), Jharkhand (0.45%), and Odisha(46.32%) subdivided into the upper, middle, and lower Mahanadi River basin, (Figure -2). The hydrogeology of the MRB consists of crystalline and soft/hard sedimentary formations and alluvial delta systems.

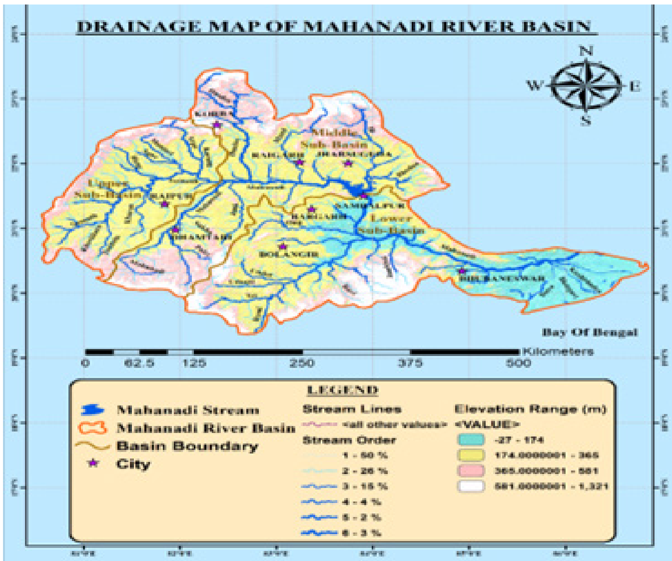


Figure 2: Classification and drainage map of the Mahanadi River basin

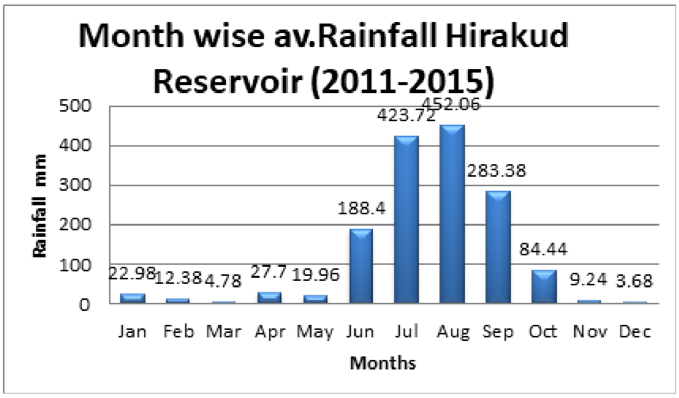


Figure 3: Monthly average rainfall in the Hirakud reservoir (source: DRIP Project; DOWR, Odisha)

Table 1: Catchment area up to Hirakud reservoir and the Mahanadi River basin (CWC data)

State	Up to Hirakud Res.		Catchment total Basin		Major Tributaries	Major Hydraulic Projects developed
	Area (Km2)	% total	Area (Km2)	% total		
Maharashtra	322	0.3	322	0.2	Sheonath	
Chhattisgarh	74970	89.9	74970	52.9	Pairi, Mond, Kelo, Hansa, Seonath, Jonk	Dams:Dudhawa, Murumsilli, Ravi-Shankar;NewRudri(B); Sikasar,Pairi, Jonk(W); Tundla; Korba (B); Minimata
Jharkhand	650	0.8	650	0.5	IB, Kelo	
M. P.	130	0.1	130	0.1	Maniyari R.	
Odisha	7400	8.8	65600	46.3	Ong, Suktel, Ib, Tel,Mand;	Hirakud
Total	83400	100	141672	100	Abb: Dc's: drains; B: Barrage D: Dam; W: weir	

Source: [35], [37];

The Hirakud catchment has an annual rainfall of 1370 mm (av. basin precipitation 1406mm) and receives about 80%of SW monsoon rain from mid-June to mid-October. The mean minimum and maximum temperatures of the basin are 10-13.70C (January) and 38- 430C in April and May [34], Table 1.

Totally 254numbers of dams, barrages, and weirs are constructed/pipelines across the Mahanadi basin or its tributaries to provide multipurpose activities like flood moderation, etc. The small dams under construction are Maharajapur, PV-133, Palachur, Pelam, Piperchedi; and Salapin Chhattisgarh state, Manjore, and Titlagarh (Stage II) in Odisha are under construction.

Flood Travel Times in UMB

Since the UMB is saucer-shaped, the flood travel time is different from streams in the canopy so the routing of the flood is an easy task (Table 2).

Table 2: Flood travel time in various reaches in UMB (Disaster mngt. plan WR, Odisha-19)

Major Nodal places	Travel time	Distance
	hours	km
Ghorari to Seorina-rayan	14	102
Nandighat to Seorina-rayan	8	104
Seorinarayan to sara-dihi	8	56
Hasdeo to Saradihi	10	80
Tarapur to Hrakud Dam	14	103

The Hirakud Reservoir

It is the composite tail dam of concrete, masonry, and earth, the longest earth dam between the Laxmidungri (left) hills and the ChandiliDunguri (right) hills in India. Hirakud reservoir cover 55 km upstream, covering 85300km2 with a dam of length 25.8 km, having 4.8km of the main dam, and the rest portion are dykes (low saddles closing) with powerhouse at Burla in the right flange. The dam has 64 sluices and 34 radial gates to discharge 8136Mm3 discharge, two head regulators for irrigation flow, and seven draft tube vents to the tailrace for outflow. The Hirakud reservoir has a live storage capacity at FRL (full reservoir level) is 5.378BCM and a mean decadal live storage capacity of 2.863BCM. There was depletion in volume on dt.25. 03. 2021 was 2.219BCM due to sedimentation and Anthropogenic activities [37]. The reservoir has a bank length of 639 km. (Table 3).

Methodologies

Damsperturb hydraulic physiognomies of velocities of flow and accelerate sedimentation. Low dams positioned outskirts of reservoirs trap mainly coarse sediment, refraining the main reservoirs from sediment. Many reservoirs are under sedimentation and have a threat of reduction of reservoir life of less than 100years. Proper basin planning and management of reservoirs, to achieve optimal sediment balance are indispensable for maximizing reservoir life. The Hirakud dam traps about one-third of sediment transported from upstream and its delta is gradually sinking, shrinking, and subsiding associated with sea level fluctuations along the delta interface, [42], [43], [29], [30],[44].Satellite data of almost nearly dates conforming to different fluvial

Table 3: The salient features/benefits received of the Hirakud multipurpose project downstream

#	Reservoir parameters	Value	#	Reservoir parameters	Value
1	Max Height Dam (MSL)	80.96m	2	Major/ total length, Dam	4.8Km/25.8 Km
3	Catchment area	83400Km2	4	Average Annual Inflow	36750Mcum
5	Water-spread (FRL) area	743 Km2	6	WS area at DSL	274 km2
7	Gross reservoir storage	8136 Mm3	8	Dead Reservoir storage	2318 Mm3
9	Net Max. Head	35.5m	10	Net min. Head	26.5m
11	Drawdown level	179.83m	12	Reservoir level (Full)	191.89m
13	Live storage capacity (Rev)	4842MCum	14	Yearly siltation 1957-89	@61.05MCum
15	Reservoirs utilized Volm	5818MCum	16	Reservoirs gross volume	8136MCum
17	Design silt index 100km2/yr	2.5 ham	18	Silt index (100 km2 /yr)	2.623 ha m
19	Flood frequency (Pre-dam)	8/decade	20	Flood freq. (post-dam)	3.3/decade
21	Kharif Irrigation	155635ha	22	Rabi Irrigation	108385
23	Capacity of reservoir	5896mcum	24	Power potential at Burla	307.5MW
25	Min. Drawdown level	179.83m	26	Full reservoir level	192.02m
27	Total live storage loss	16.9%	28	Yearly storage loss	0.376%
29	Safe discharge by 64sluces	26885cumec	30	Disch. (34 radial gates)	15565Cumec

Source: [38], [39], [40], [41].

stages are cast off to appraise the lacustrine areas. The ratio of NIR/RED images was created to detect the water pixels, and later the normal FCC was under verification after removing the non-water pixels (green/NIR ratio). The area under water and the related elevations applied in finding the reservoir storage capacity from the Area-Elevation curve.

The IDW (inverse distance weighted) Maps and Raster Maps are exported into a different layer for further processing and then compared using the surface tool under Arc Toolbox to exhibit the results. Further, the attribute values are obtained from the difference maps/data exported into an MS Excel file. The exported data is analysed to obtain through Digital Elevation Model (DEM), for making contour maps, slope maps, aspect maps the water spread area maps for evaluating sediment deposition during a particular span. Analysis and comparison by using the contouring toolbar applied to Elevation Analysis, Tabular Analysis and Stream Order Analysis are fruitful.

CWC has categorized the life span of reservoirs into five phases. Phase-1: Full-service period: utilizable up to designed capacity, Phase-II: Feasible service period: operational and economical, Phase-III: Extensible service period: higher sedimentation, difficult to operate due to clogging of sluices. Phase-IV: impossible to operate: uneconomical requiring renovation, Phase-V: exhausted life span, totally non-operational, demands re-planning, reallocating-design, and renovation. It is desired the sedimentation should remain at optimal levels (stage II).

Morphometric analysis

The drainage flow network of the basin area facilitates basin managers' morphometric, and geo-morphologic analyses, for efficient hydrologic modelling, water resources planning, and flood and non-point pollutant source simulation, [45]. The Ldd net (local drain direction net), depicts the anastomosis, and hierarchy of the drainage basin delineation of real resources in the system obtained from the contour maps. The UMB is sloping mostly from north to south with broken-up hills of height falls from 173.73m in the north until the bed at Sambalpur to 146.34 M, (Fig 2), [18]. The drainage patterns in the UMB sub-basins are sub-dendritic to dendritic with low drainage density, permeable subsoil, and thick forests.

The stream ordering map and bifurcation ratio

The hydrology application from spatial analysis, the Arc GIS, tools used considering the SRTM data. The flow direction of the drainage channels was identified. Later the flow accumulation and input data are selected, and the stream feature in layers. The flow direction was determined after adding the raster calculation. Bifurcation Ratio (Rb1), calculated

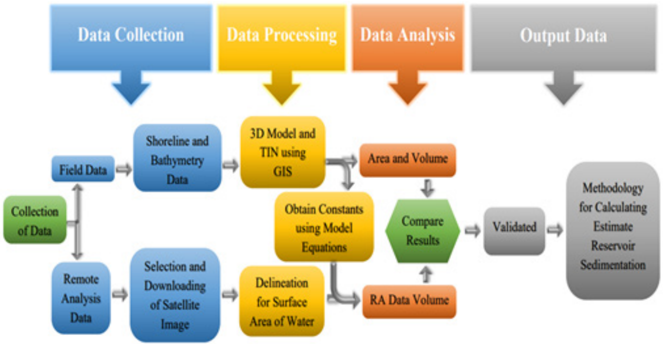


Figure 4: GIS methodology of sedimentation calculation of Hirakud reservoir

considering the 1st, and 2nd order stream = Number of streams for 1st order (N1) / Number of streams for 2nd order (N2). ∑Rb= (R(b,1) + R(b,2)+ R(b,3)+ ……+ R(b,n)]/n⟧ Where, n= stream order number. GIS-web was used to evaluate linear, areal, and relief aspects of morphometric parameters of Hirakud Reservoir by knowing the flow direction, length, accumulation, and flow along with stream ordering and bifurcation ratio (Table 4) and (Fig 5).

The high bifurcation ratio, ranging between 2 and 4 indicates that the geologic formations of the area have not been affected by distortion of the drainage pattern [46]. The stream order (morphometric analysis) can identify and classify the types of streams depending on the number of tributaries. The morphometric analysis helps the bio-geographers and biologists in deciding on the drainage channels, and their erosion

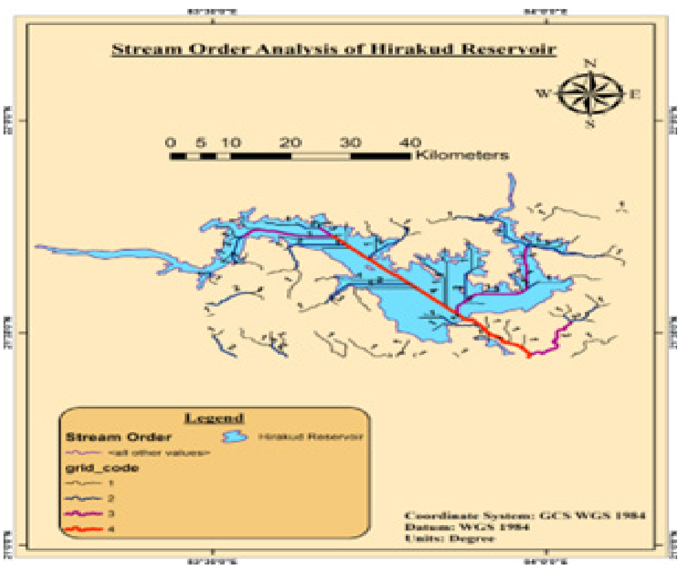


Fig 5: The stream order of the Hirakud reservoir (Mahanadi upper basin)

capabilities in the area that may influence planning hydraulic structures and watershed management [47] [4], [48][49], [47], [50].

Table 4: Number of streams, stream order, and the bifurcation ratio of the Hirakud reservoir

Stream Order	Streams (Numbers)	Slope (Sen D et al. 2019[43])	Bifurcation Ratio (Rb)	Average Rb value
First order	85	Rajim (6:10000)	2.361	1.92
Second order	36			
Third order	12	Seorinarayan (4:10000)	03	
Fourth order	20	Tikarpara (2:10000)	0.4	

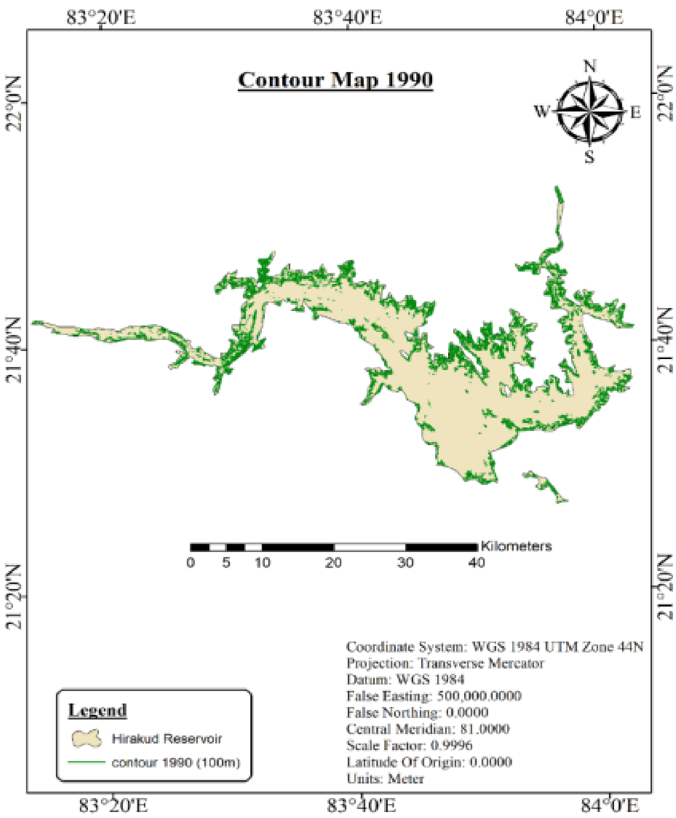
Contour Map generation

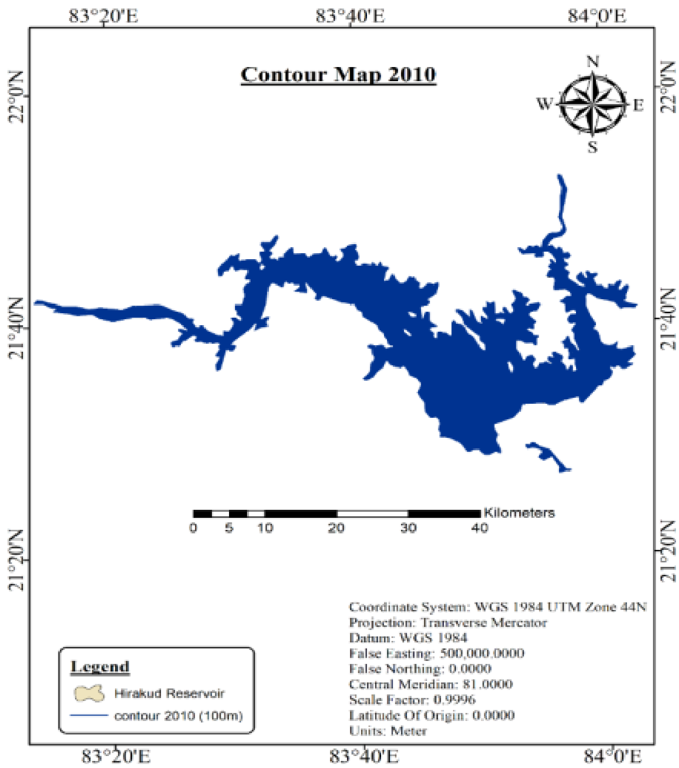
In Arc GIS Map, a digital elevation model (DEM) need slope profiles that generate the files or maps containing contour by using the contouring toolbar. A slope map was created from the DEM layer. The contour maps are topographic and configure relief features of an area. In the case of reservoir sedimentation, the isohyets lines in these layers depict the position of geospatial changes in the deposition of sediment in the bed. The contour maps were pointed to the flow channels within the reservoir. The path of sediment generally discharges from the tail cluster to emanating sections [51].

Slope Mapping

Slope and aspect-slope maps can be possible by ArcGIS Pro by checking the ArcGIS Online account and raster function. The specification of a z-factor is assigned if the z units are in a different unit than the X and Y ordinates. Aspect mapping is possible by adding elevation data to the map. Assure ArcGIS Spatial Analyst enabled by creating a new project using the aspect map template using a raster function.

The slope map is a topographic plan prepared from DEM that shows elevation changes in the real world. Architects, town planners, and basin managers use the slope map to evaluate the altitude and other attributes of a particular site for future planning of water resources, urban architecture, and other land-related projects. The bottom slope of the reservoir carrying sediment changes with flood flow velocities, landslides, earthquake tremors, the shape of the canopy, size of sediment, rate of sediment loading, and intermittent anthropogenic interventions (Fig 7 a, b, c, d, e, f, g).


Contour Map 1990
N
S
E
W
83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
0 5 10 20 30 40
Kilometers
Coordinate System: WGS 1984 UTM Zone 44N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 81.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
Legend
Hirakud Reservoir
contour 1990 (100m)


Contour Map 2010
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83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
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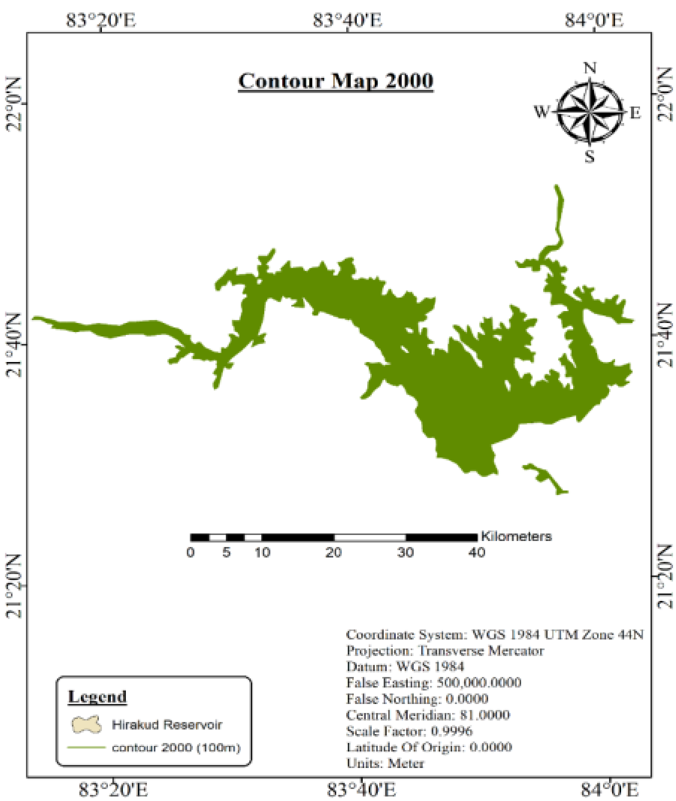
Kilometers
Coordinate System: WGS 1984 UTM Zone 44N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 81.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
Legend
Hirakud Reservoir
contour 2010 (100m)


Contour Map 2000
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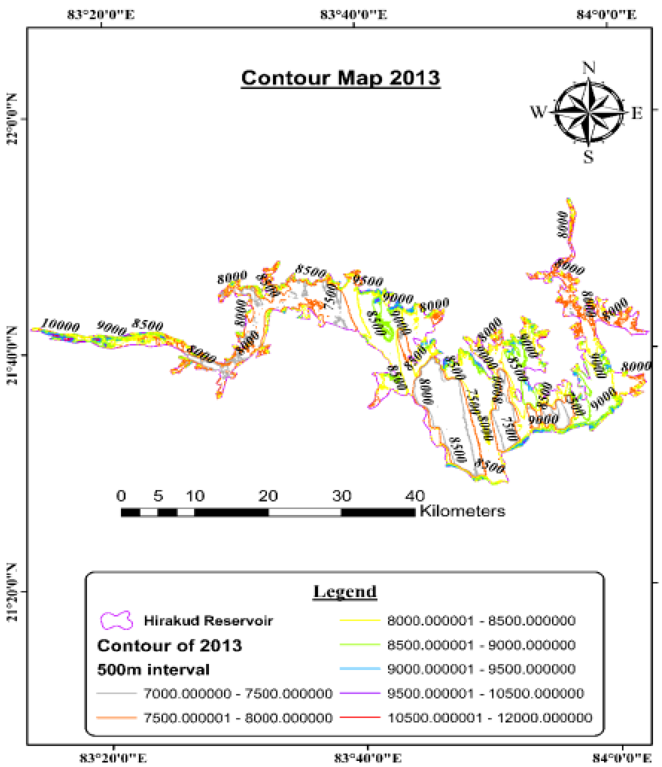
83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
0 5 10 20 30 40
Kilometers
Coordinate System: WGS 1984 UTM Zone 44N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 81.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
Legend
Hirakud Reservoir
contour 2000 (100m)


Contour Map 2013
N
S
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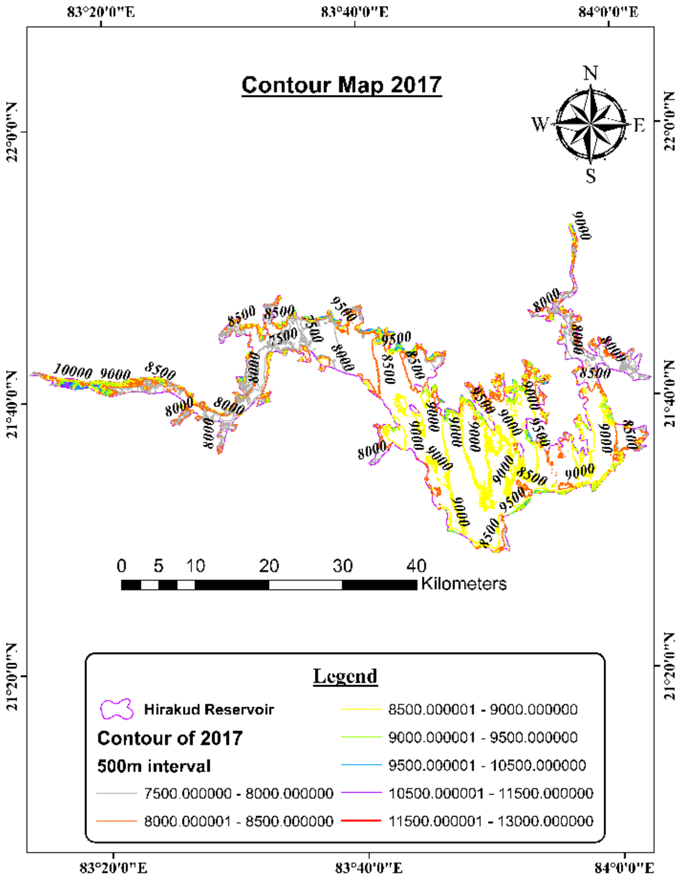
83°20'0"E
83°40'0"E
84°0'0"E
22°0'0"N
21°40'0"N
21°20'0"N
0 5 10 20 30 40
Kilometers
Legend
Hirakud Reservoir
Contour of 2013
500m interval
7000.000000 - 7500.000000
7500.000001 - 8000.000000
8000.000001 - 8500.000000
8500.000001 - 9000.000000
9000.000001 - 9500.000000
9500.000001 - 10500.000000
10500.000001 - 12000.000000



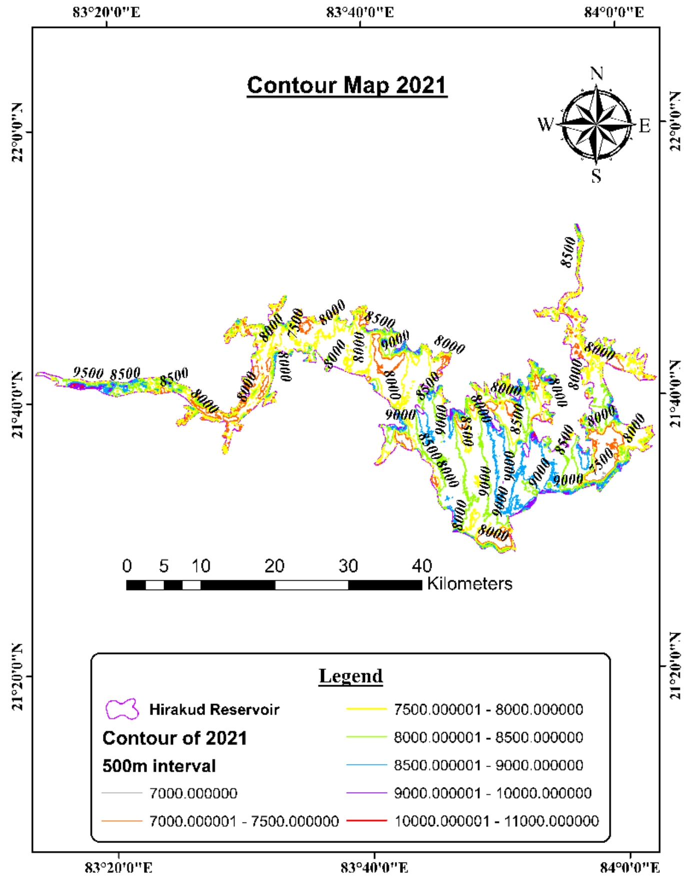
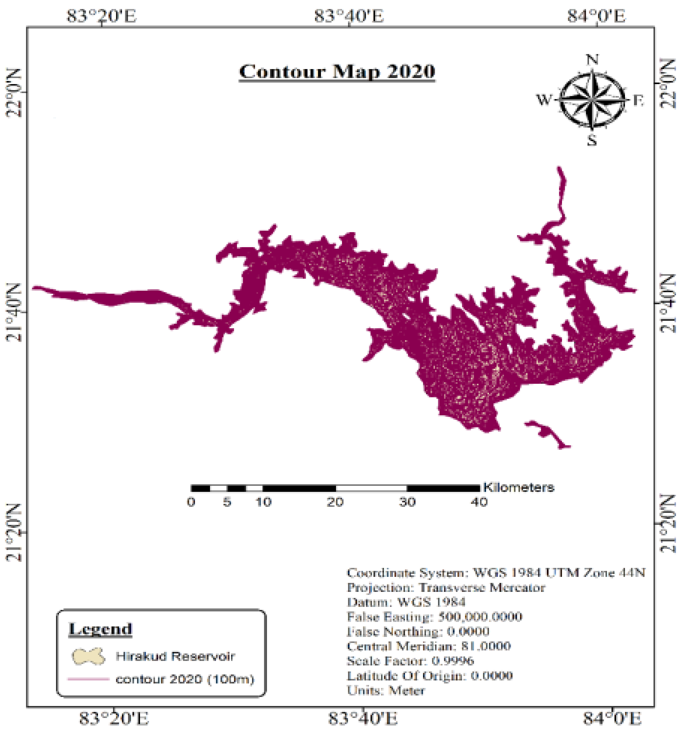
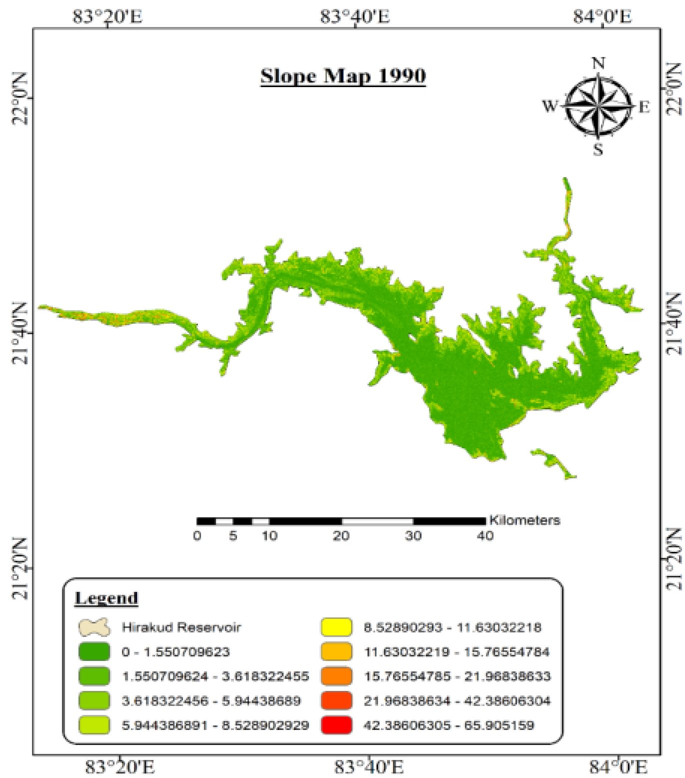
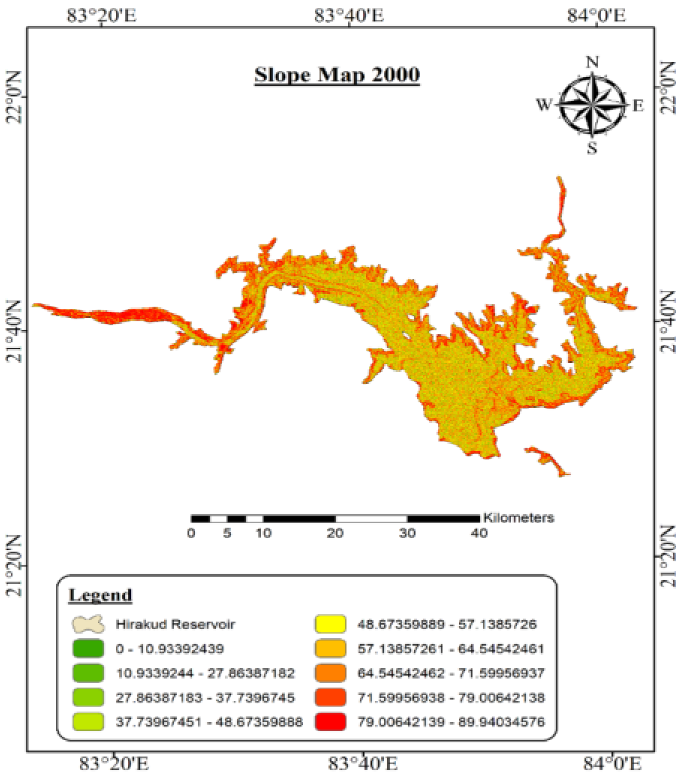


Figure 6 (a, .. g): Contour Map of Hirakud reservoir (1990, 2000, 2010, 2013, 2017, 2020, 2021)






Slope Map 2000
83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
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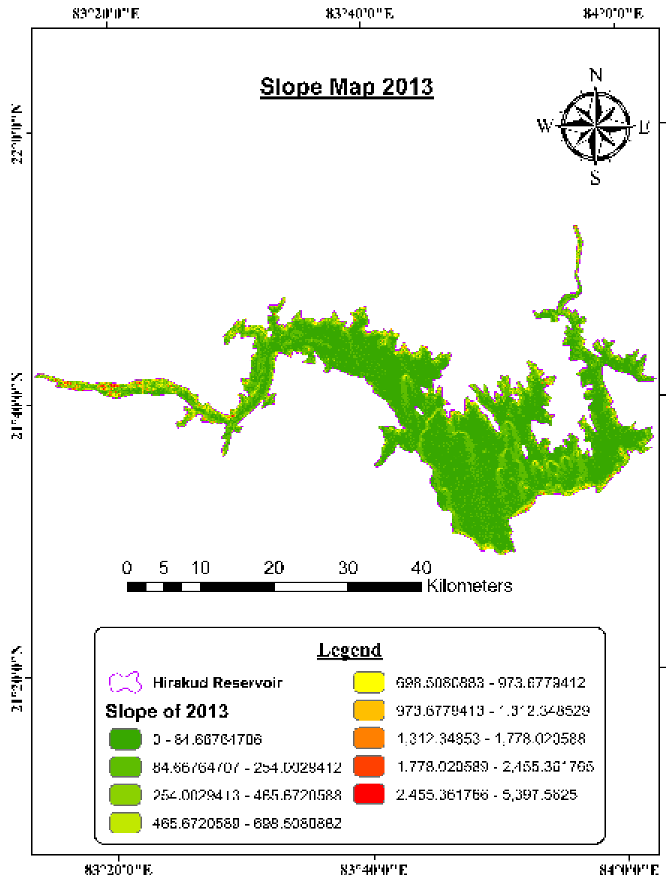
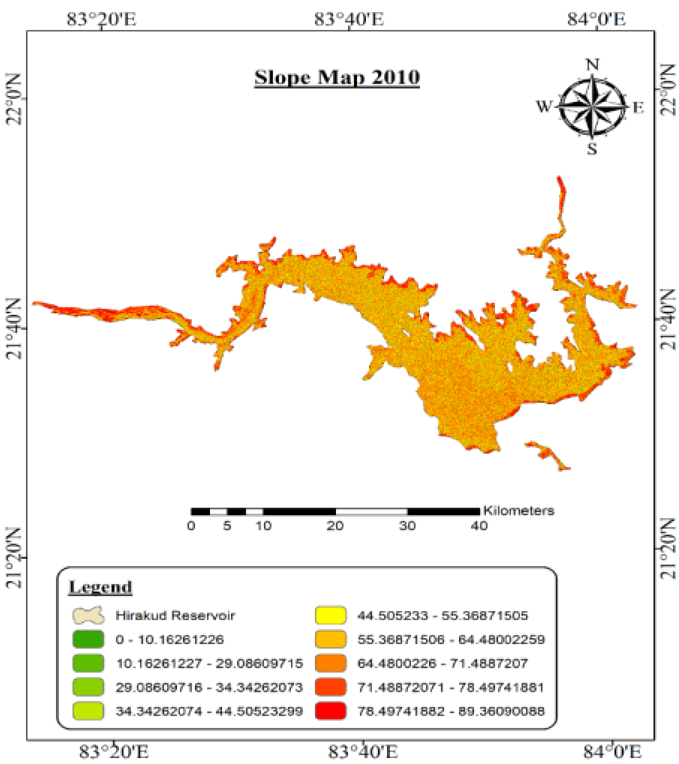
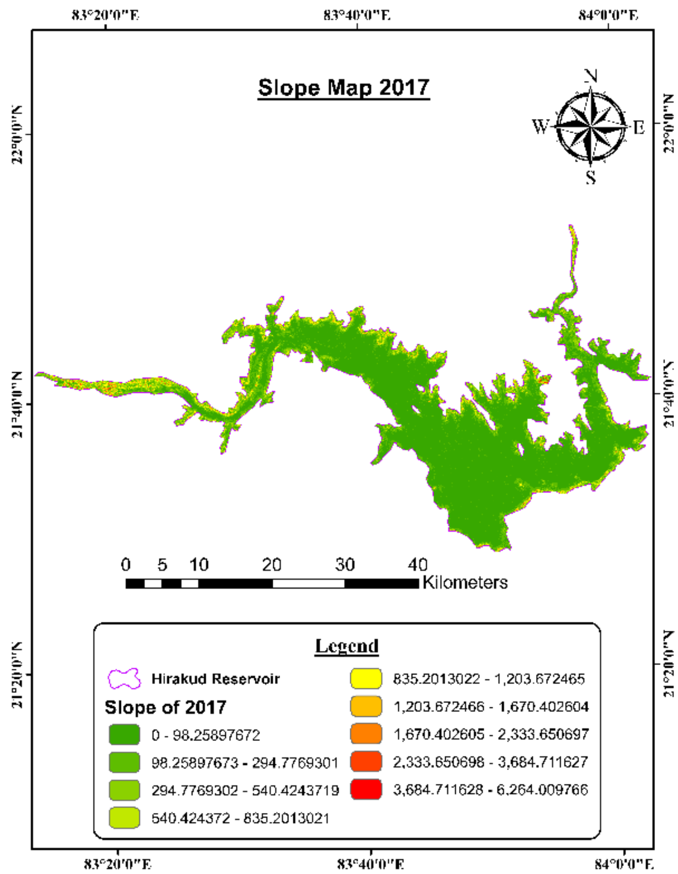
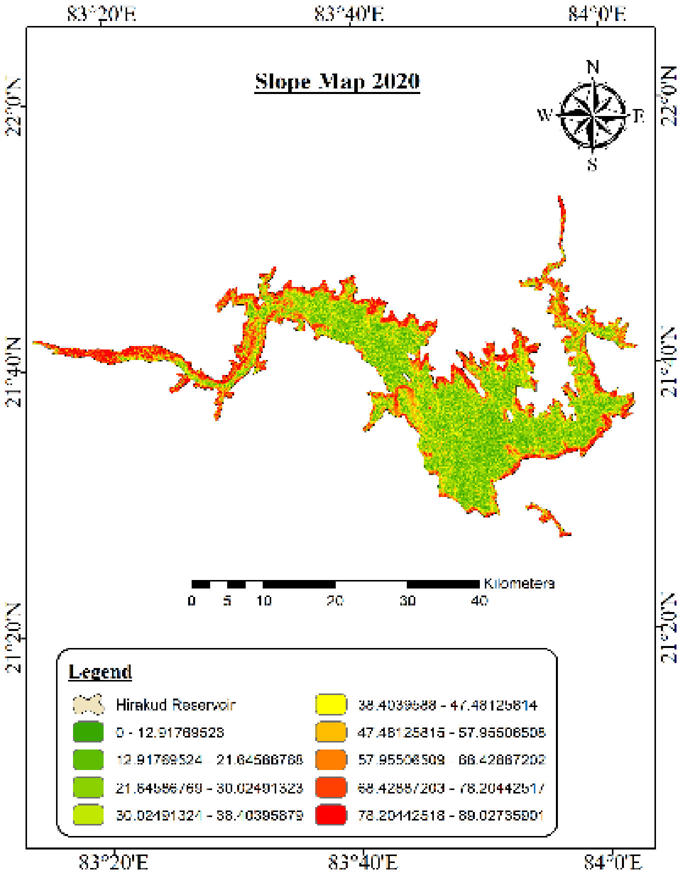
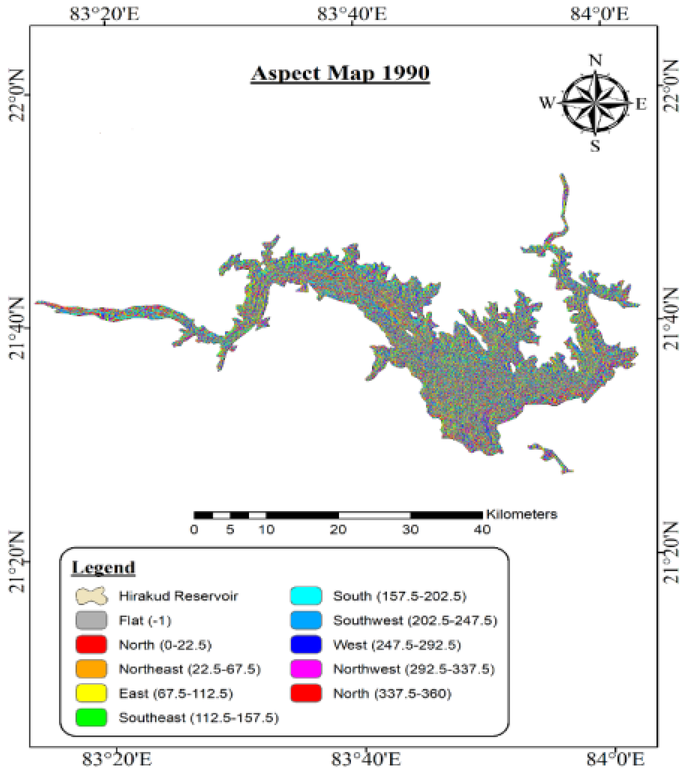
Kilometers
0 5 10 20 30 40
Legend
Hirakud Reservoir
0 - 10.93392439
10.9339244 - 27.86387182
27.86387183 - 37.7396745
37.73967451 - 48.67359888
48.67359889 - 57.1385726
57.13857261 - 64.54542461
64.54542462 - 71.59956937
71.59956938 - 79.00642138
79.00642139 - 89.94034576

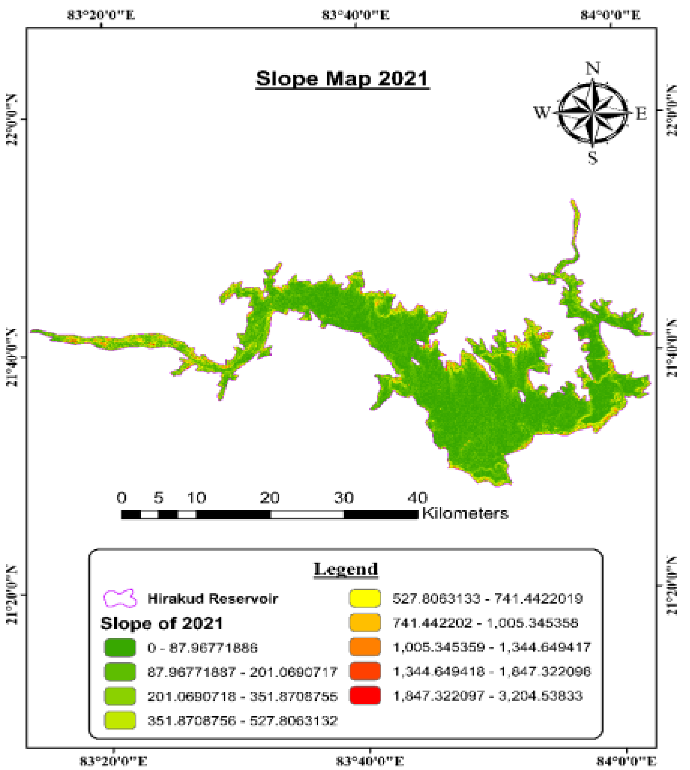

Slope Map 2013
N
W
E
S
0 5 10 20 30 40
Kilometers
Legend
Hirakud Reservoir
Slope of 2013
0 - 84.66764706
84.66764707 - 254.0029412
254.0029413 - 465.6720588
465.6720589 - 698.5080882
698.5080883 - 973.6779412
1,312.34853 - 1,778.020588
2,455.361766 - 5,397.5625


Slope Map 2010
83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
N
W
E
S
Kilometers
0 5 10 20 30 40
Legend
Hirakud Reservoir
0 - 10.16261226
10.16261227 - 29.08609715
29.08609716 - 34.34262073
34.34262074 - 44.50523299
44.505233 - 55.36871505
55.36871506 - 64.48002259
64.4800226 - 71.4887207
71.48872071 - 78.49741881
78.49741882 - 89.36090088


Slope Map 2017
83°20'0"E
83°40'0"E
84°0'0"E
22°0'0"N
21°40'0"N
21°20'0"N
N
W
E
S
0 5 10 20 30 40
Kilometers
Legend
Hirakud Reservoir
Slope of 2017
0 - 98.25897672
98.25897673 - 294.7769301
294.7769302 - 540.4243719
540.424372 - 835.2013021
835.2013022 - 1,203.672465
1,203.672466 - 1,670.402604
1,670.402605 - 2,333.650697
2,333.650698 - 3,684.711627
3,684.711628 - 6,264.009766







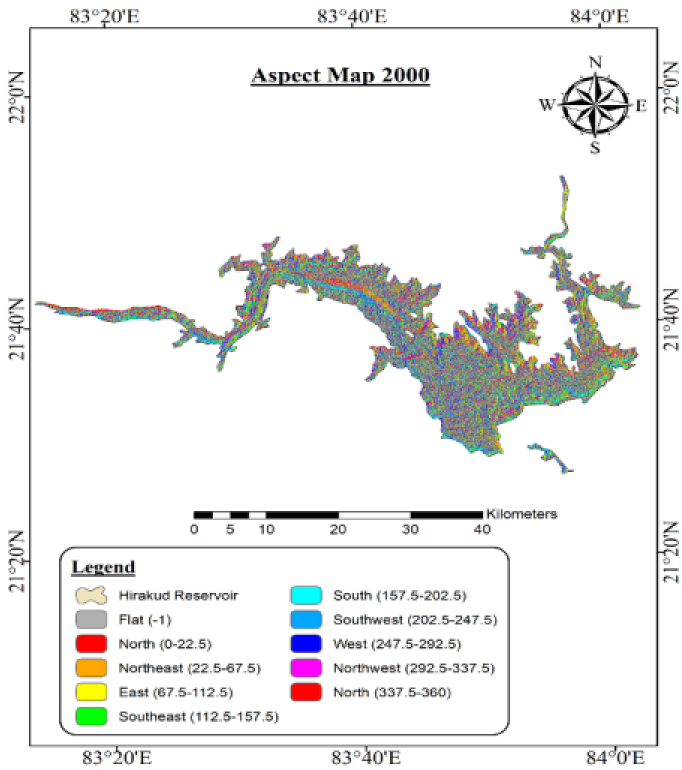
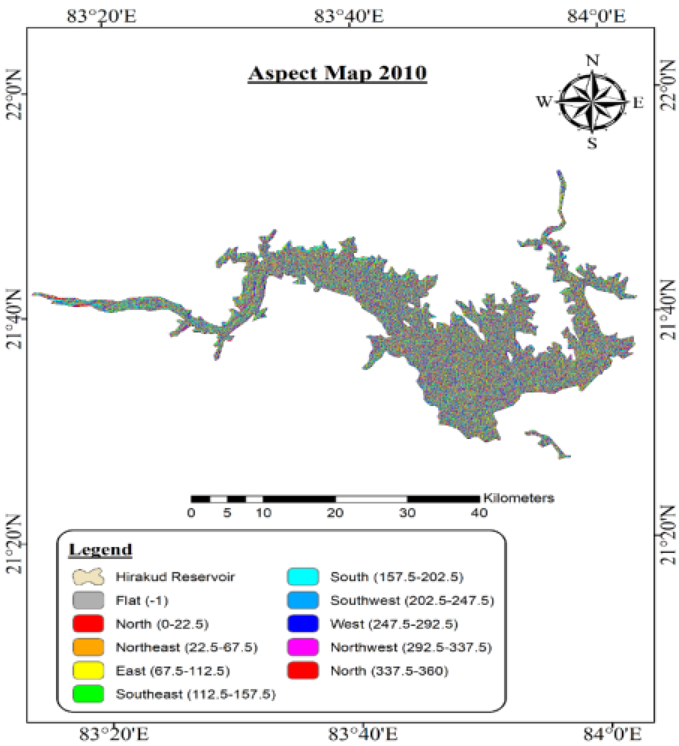
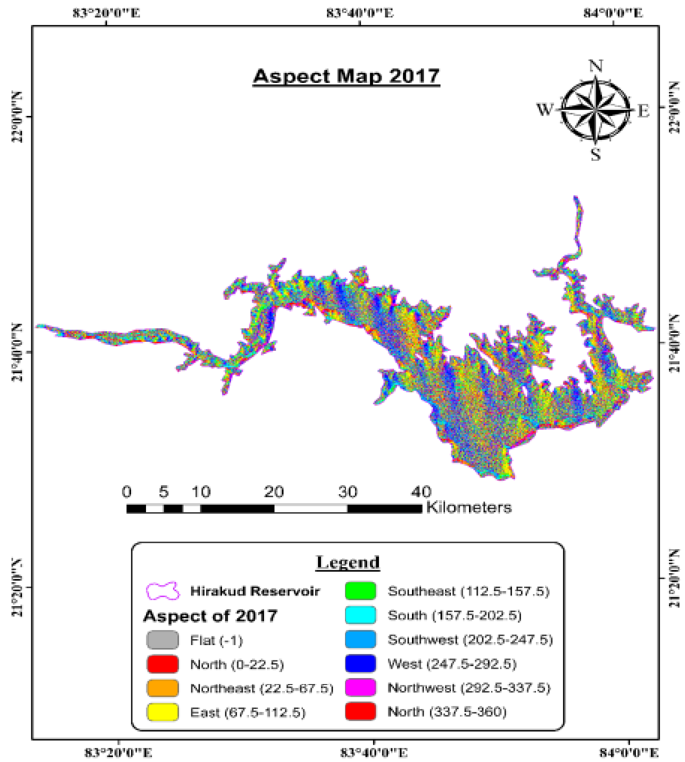
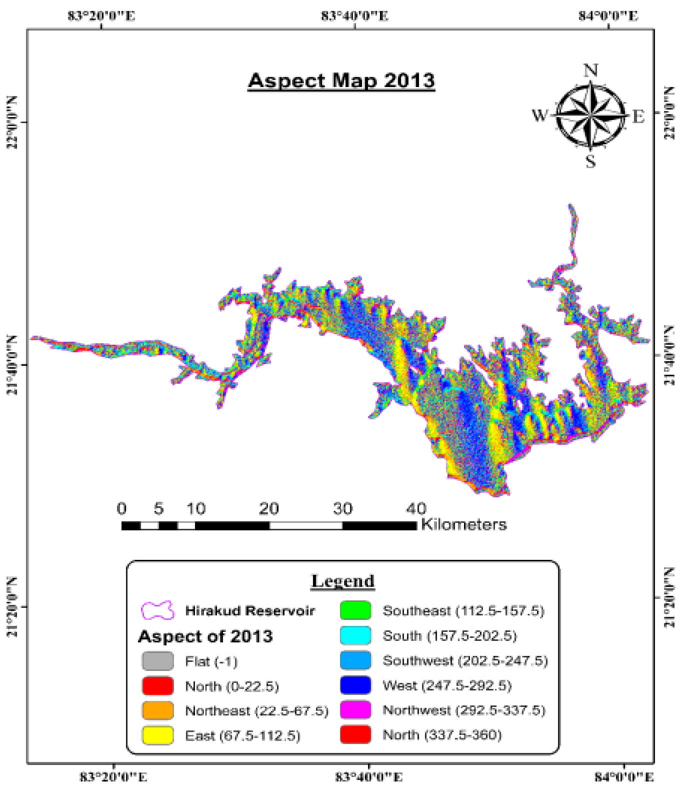
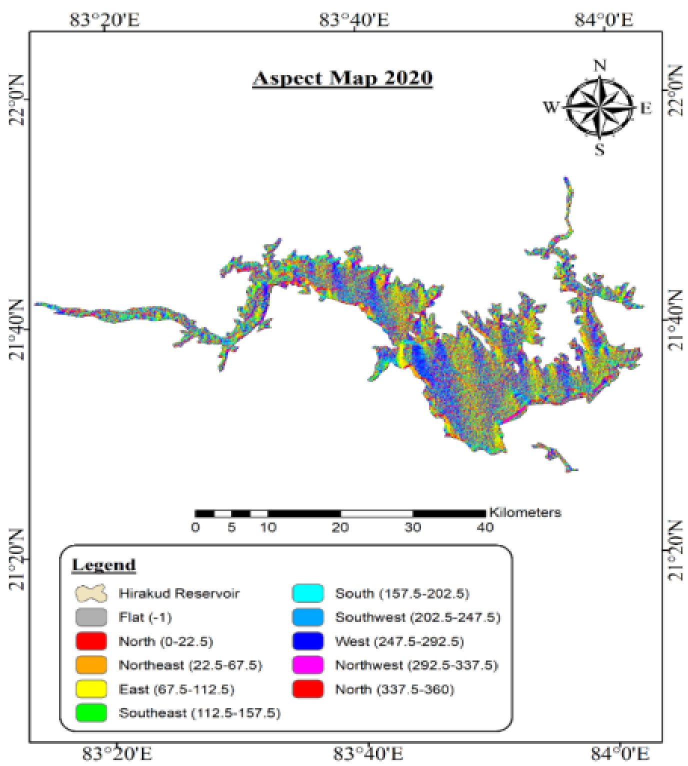


Figure 7 (a, b, c, d, e, f, g): Slope Map of Hirakud reservoir for the years 1990, 2000, 2010, 2013, 2017, 2020 and 2021


Aspect Map 2010
83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
N
S
E
W
0 5 10 20 30 40 Kilometers
Legend
Hirakud Reservoir
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)


Aspect Map 2017
83°20'0"E
83°40'0"E
84°0'0"E
22°0'0"N
21°40'0"N
21°20'0"N
N
S
E
W
0 5 10 20 30 40 Kilometers
Legend
Hirakud Reservoir
Aspect of 2017
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)


Aspect Map 2013
83°20'0"E
83°40'0"E
84°0'0"E
22°0'0"N
21°40'0"N
21°20'0"N
N
S
E
W
0 5 10 20 30 40 Kilometers
Legend
Hirakud Reservoir
Aspect of 2013
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)


Aspect Map 2020
83°20'E
83°40'E
84°0'E
22°0'N
21°40'N
21°20'N
N
S
E
W
0 5 10 20 30 40 Kilometers
Legend
Hirakud Reservoir
Flat (-1)
North (0-22.5)
Northeast (22.5-67.5)
East (67.5-112.5)
Southeast (112.5-157.5)
South (157.5-202.5)
Southwest (202.5-247.5)
West (247.5-292.5)
Northwest (292.5-337.5)
North (337.5-360)

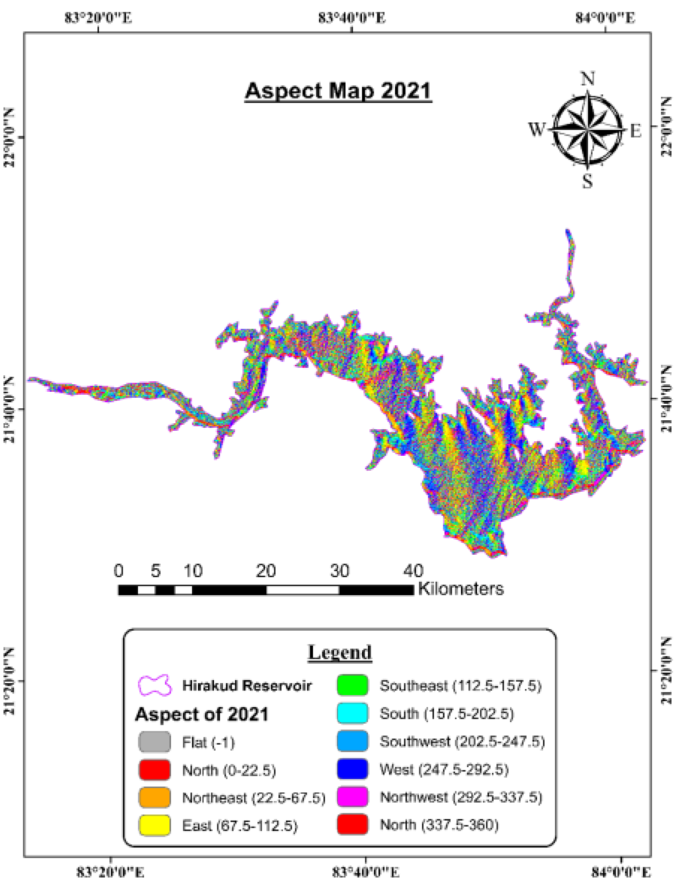


Figure 8 (a, b, c, d, e, f, g): The Aspect Map of Hirakud reservoir for the years 1990, 2000, 2010, 2013, 2017, 2020 and 2021

The Aspect map:

Aspect raster maps designate the values of the directions of the slope classes at faces based on the angle of slope and degree of terrain slope. Aspect classes are signified by colors like red, orange, yellow, etc., and the degree of slope classes indicated by saturation or showing the steeper slopes are brighter [52].

The aspect map through coloring indicates that both the degree and angle of the terrain slopes are different in the years 1990, 2000, and 2010. The change in terrain slope is prominent for the years2010, 2013, 2017, 2020, and 2021.

Past sedimentation survey

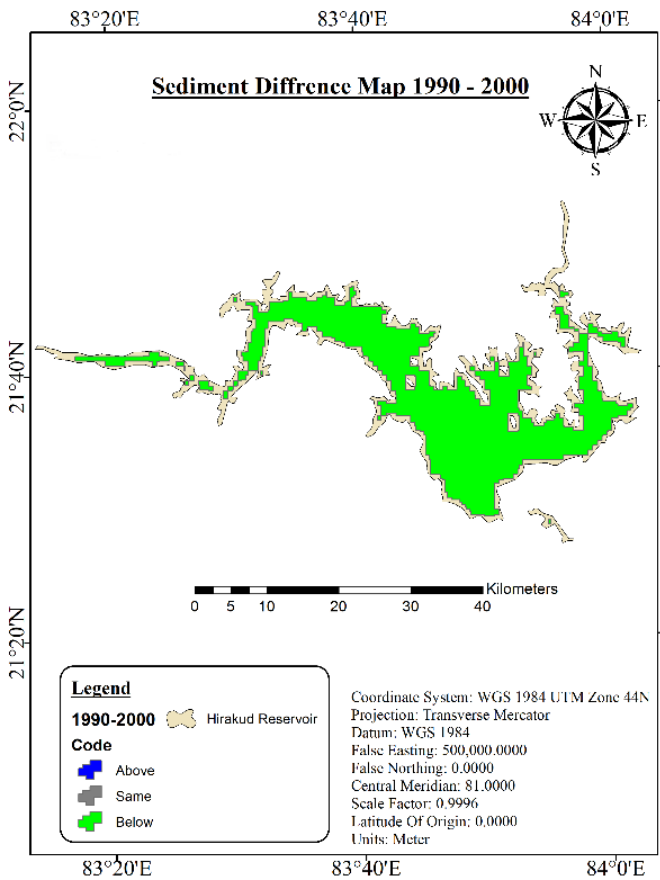
Dams interrupt flow continuity during the transport of sediment and get trapped. Sediment surveys are pertinent to impart knowledge about the trend of sedimentation to reschedule storage for efficient reservoir operation and fix new zero elevation if needed. The first impoundment in the Hirakud reservoir was in 1957. Sedimentation surveys were conducted in four stages during 1979, 1982, 1986, and 2005, [28], and the last study was done by CWC in 2005.

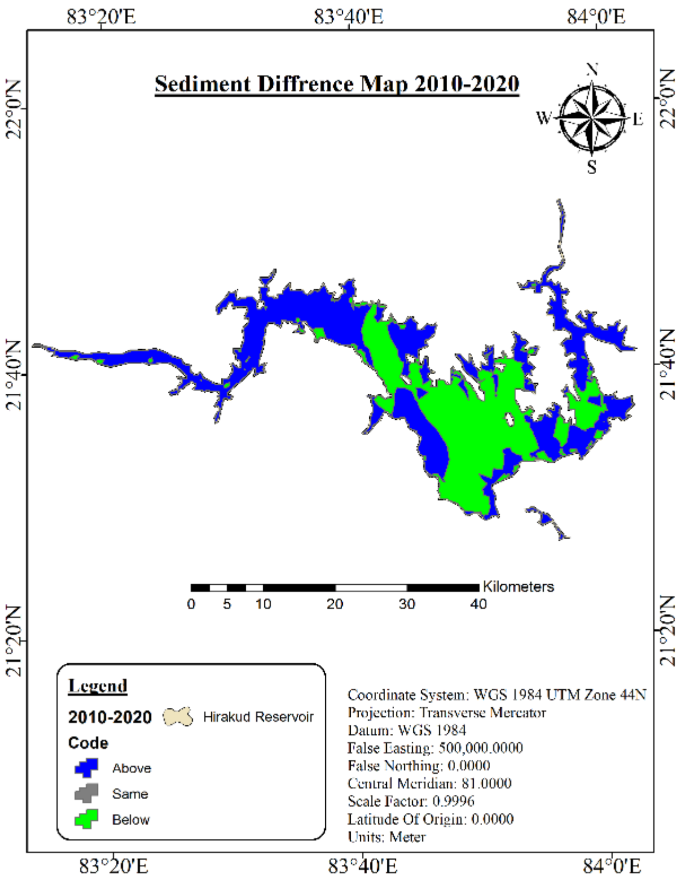
Present sediment difference map

The capacity of a reservoir between two consecutive altitudes is assessed by the Cone formula:

$$V= \Delta H(A_1+ A_2+ A_1{}^* A_2)/3$$

Where V = Volume / Capacity between two adjacent elevations, A1 and A2 = Water spread at those elevations respectively, Δ H = elevation difference at1 and 2. The sum of the successive volumes gives the cumulative capacity between two consecutive layers. In the GIS methodology, after site selection and acquisition of Landsat digital data, the band's available data set is combined in the composite





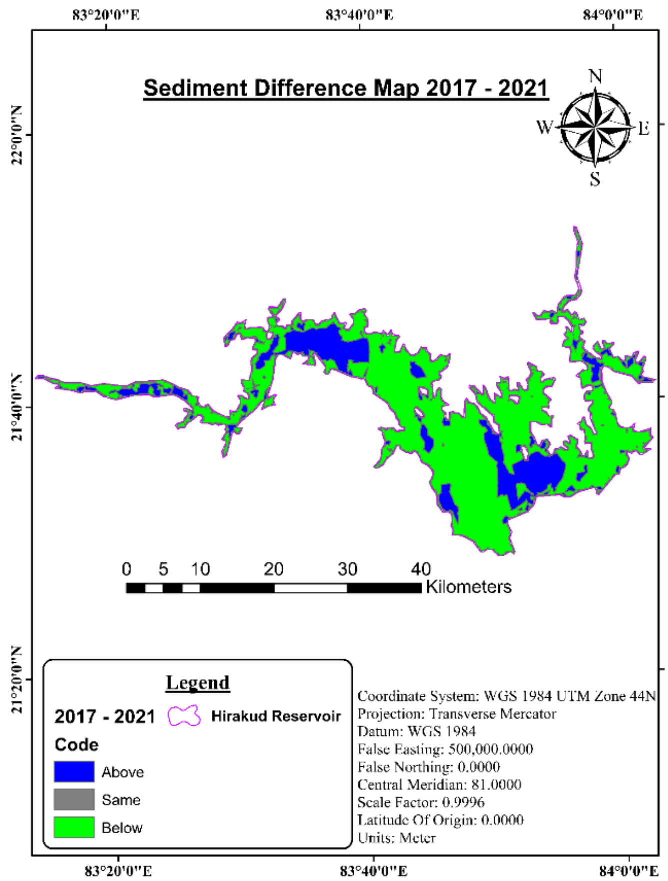
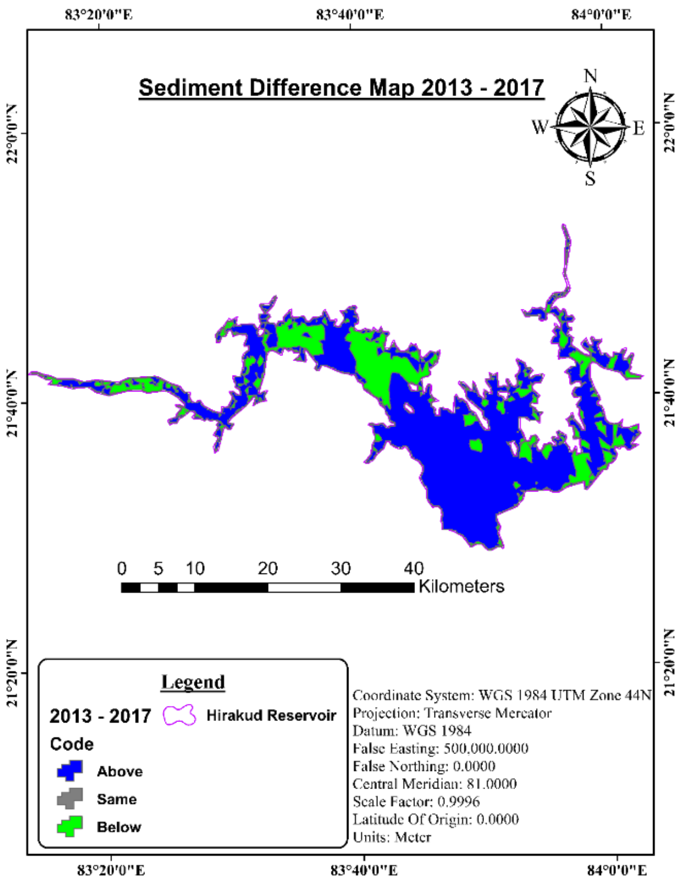


Fig 9 (a, b, c, d): Sediment difference map 1990-2000, 2010-2020, 2013-2017, and 2017-2021 of Hirakud reservoir.

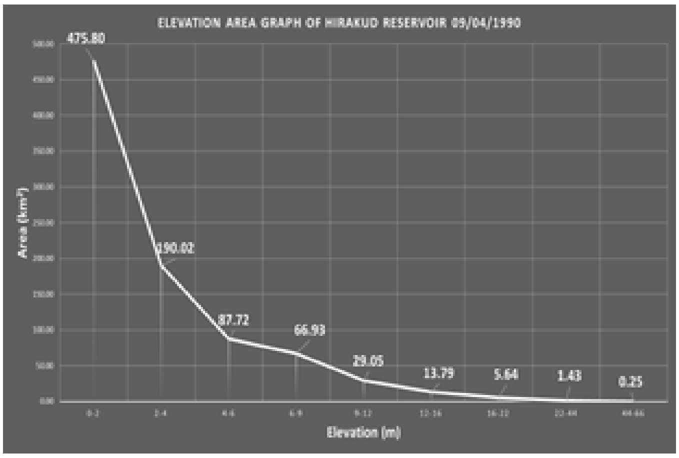


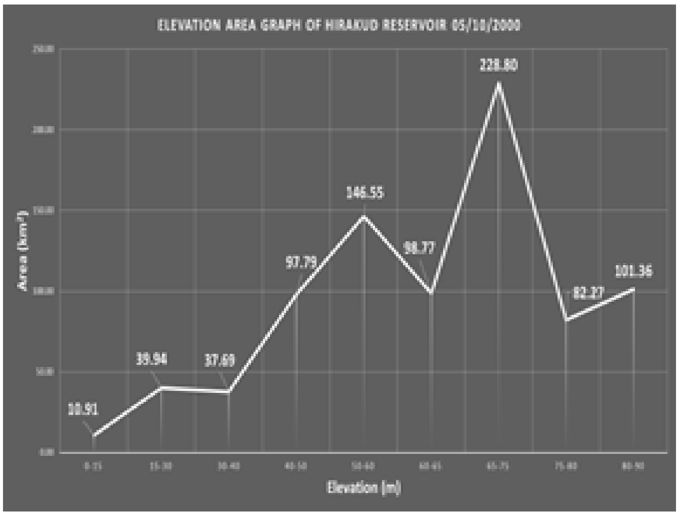
maps (topographical to Raster) created. Using the elevation data, the contour map of the study area was generated, and the IDW (inverse distance weighted) map was made using the interpolation tool under Arc Toolbox.

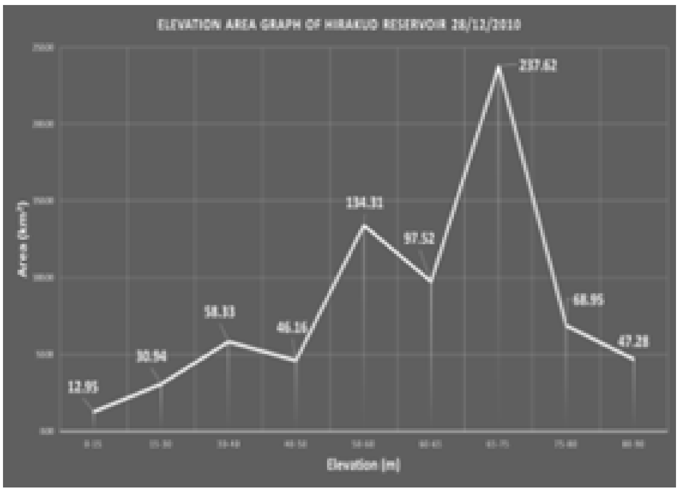
The IDW Maps and Raster Maps are exported into a different layer for further processing. All the exported files were then converted, using the conversion tool under Arc Toolbox, to TIN (Triangulated Irregular Network) format. The TIN formatted Maps were compared using the surface tool under Arc Toolbox. Post-comparison, a difference map was created to show the results. The sediment difference map for1990-2000, 2010-2020, 2013-2017, and 2017-2021 are shown in (Fig 9(a), Fig 9(b), Fig 9(c)and Fig 9 (d). The MRB has gone through a continuous dry spell in the catchment and the main body of the reservoir. So the resevoir has shown high sedimentation for the period 2013-2017. The normal rainfall reiterated for the period 2017 to 2021 has surpassed the sedimentation phase and the reservoir maintained sustainability.

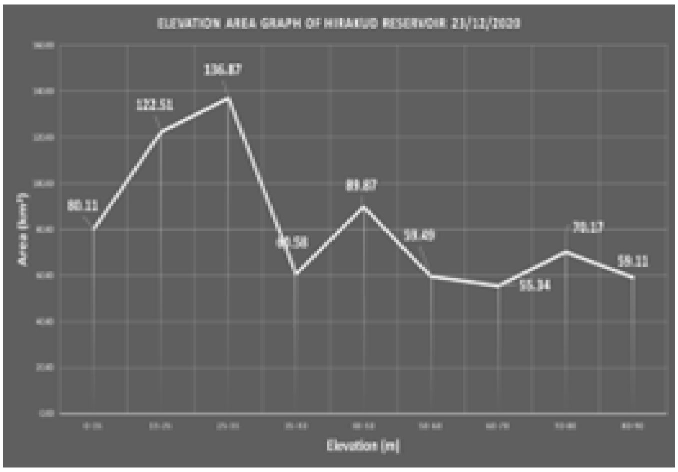
Table 5: Various elevation ranges, and lacustrine areas during 1990, 2000, 2010, 2020, and 2021

Elevation Range (m)	Area (km²) 1990	Elevation Range (m)	Area (km²) 2000	Area (km²) 2010	Area (km²) 2020	Area (km²) 2021
0-2	475.80	0-15	10.91	12.95	80.11	63.11
2-4	190.74	15-30	39.94	30.94	122.51	100.27
4-6	87.72	30-40	37.69	58.33	136.87	126.58
6-9	66.93	40-50	97.79	46.16	60.58	136.46
9-12	29.05	50-60	146.55	134.31	89.87	96.32
12-16	13.79	60-65	98.77	97.52	59.49	90.36
16-22	5.64	65-75	228.80	237.62	55.34	65.96
22-44	1.43	75-80	82.27	68.95	70.17	41.35
44-66	0.25	80-90	101.36	47.28	59.11	5.54









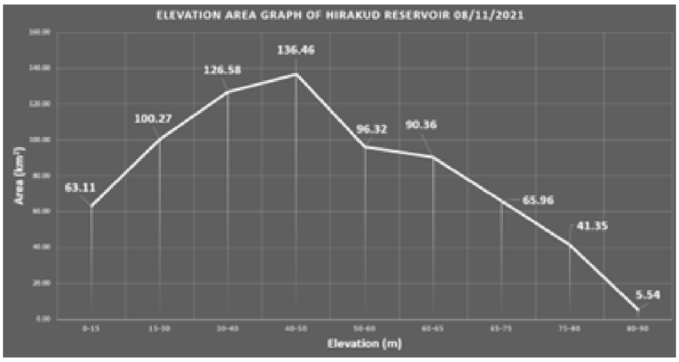


Fig.10 (a, b, c, d, e): Elevation-Area curve of Hirakud reservoir (1990, 2000, 2010, 2020, 2021)

Elevation vs. Area

Area capacity curves or elevation area curves are necessary to assess the quantity of sediment deposited within the artificial lake showing elevation ranges and lacustrine area, (Table 5).

Resulting Elevation-Area Map

Landsat 4-5 Thematic Mapper (TM) images have seven spectral bands with a spatial resolution of 30 meters for Bands 1 to 5 and 7. The spatial resolution for Band 6 (thermal infrared) is 120 meters but

Table 6: Sedimentation Volume and water spread area of the reservoir in the last 3 decades.

Years	Calculated Volume of Reservoir	Catchment Area of UMB	Water-spread area	Calculated Siltation	Calculated Scouring	Total Vol sediment accrued
	(MCM)	(Km^2)	(Km^2)	(MCM)	(MCM)	(MCM)
1990-2000	6012	85,997.12	674.36	142	5960	5818
2010-2020	5975	87,917.34	661.98	4233	1641	2592
2013-2017	5868	86,060.59	656.07	5386	482	4904
2017-2021	5890	84,142.85	667.93	629	5261	4632

Table 7: Base reservoir volume/ UMB area data Hirakud reservoir from the last survey in 2000

Years	Calculated Volume (MCM)	Catchment Area of UMB(Km^2)	Calculated Siltation (MCM)	Calculated Scouring (MCM)
2000	5818	83,395	NIL	NIL

Table 8: Error calculation w.r.t Table 7 data

Years	Volume	Calculated Area
1990-2000	3.33%	3.12%
2010-2020	2.69%	5.43%
2013-2017	0.85%	3.19
2017-2021	1.23%	0.89

presently resampled to 30-meter pixels. The present study reveals data acquired is old and inconsistent compared to the latest Landsat 8-9 data. Errors have been incorporated during the analysis of the elevation in 1990. Landsat 5 data was acquired from 15th June 2001. The elevation capacity curves indicate that up to the year 1990 was normal; as the reservoir behaved as in Phase I stage and later the reservoir moved to stage II. The data recovered from Landsat-5 until 2010 have missing error files. So the Landsat-8 data for the years 2013, 2017, 2020 and 2021was later analyzed to achieve a conclusive result in Fig 10 (a,b,c, d, and e).

Error calculation

Error Calculations have been done based on the data acquired from CWC/State survey files, in our case from the year 2000, and the volume, area, and accumulation data were compared to that of ours which was obtained from satellite analysis. A simple percentage calculation process was followed and our data has been compared to the last surveyed data. The resulting data reveal the errors/changes over the last 3 decades (4- phases), keeping the last surveyed data as a reference.

The sediment deposition pattern shows that the 1st and 2nd-period sedimentation occurred in the usable storage capacity (active zone) whereas from 2010 to 2020 the sediment accruing occurred in the conservation zone encroaching utilities of the reservoir. A rough quantization of the sedimentation of the Hirakud reservoir is in Tables 6, 7, and 8.

Discussion

Presently, India has 5254 completed and 411pipeline dams with gross storage of more than 300 BCM. About 80% of operating dams have exceeded 25 years. The health, stability, and safety of the dam and its appurtenant structures are important for the sustenance of the dam, reservoirs, and utilities. For the life/safety of the dam users and property/lives in the downstream areas, it is pertinent to investigate existing management, operation, and maintenance practices judiciously.

The type of sediment carried by the Mahanadi River during the preconstruction of Hirakud dam (1947) was 76% suspended particles, (≤0.075mm), medium and 13% (0.075 mm< d< 0.2mm) and balance 11% were sand particles of size ≤ 0.2mm [53]. As per CWC, the Hirakud reservoir sedimentation is following the deltaic theory articulated by Col. Ellis wherein the sedimentation of the reservoirs follows three stages (a) initially the silt accumulated up to the sill of sluices followed by the formation of a channel by river route and finally, there is a slow deposit of silt thereafter. The quantum of sediment pledge in the reservoir area is proportionate to the standing water flowing over the area [2].

Table9: The past sedimentation studies of Hirakud reservoir, Odisha in the Mahanadi Basin,

#	Study year	Original cap./ capacity/ Mm3)/ Km2	% Av. Loss gross Cap.	Av yearly capacity loss/	Reference
1	1957/1989 (23yrs)	Gross live 5826 Mm3/8136/ Mm3 1957	16.9%	0.376 % of live storage or 21.9 Mm3/ year-1	Rathore et al., 2006[12]
2	1957-1979 (22years)	Storage cap: 8105 to 6934.26Mm3	14.44%	Loss of gross capaci-ty1170.74 by state Govt	CWCcomp-endium 2020[39]
3	1979-1981 (2years)	Storage cap: 6934.26 to 6626.41 Mm3	3.8%	Loss of gross capaci-ty1478.59 by state Govt	CWCcomp-endium 2020[2]
4	1981-1986 (5years)	Storage cap: 6626.41 to 6613.76 Mm3	0.16%	Loss of gross capacity 1491.24 by state Govt	CWCcomp-endium 2020[2]
5	1957/1989 (23yrs)	Gross storage 8136/ 6151.30 Mm3	24.1% loss	@ 61.05 Mm3/yr;	Mukherjee et al., 2007[24]
6	1986-1991 (5years)	Storage cap: 6613.76 to 6210.00 Mm3	4.98%	Loss of gross capacity 1895.00 by state Govt	CWCcomp-endium 2020[2]
7	1991-2000 (9 years)	Storage cap: 6210.00 Mm3 to5894.795	3.89%	Loss of gross capacity 210.21 by state Govt	CWCcomp-endium 2020[2]
9	1957-2001 (44years)	Live 5826Mm3 in 1957	17%;(@0.376%/ year	5106. 4901, 4842Mm3 in 1986, 1995, and 2001	Togabe et al., 2014[40];
10	1957-2020 (63years)	Live storage in 6012MCM at FRL/MWL/192.024m in 2000 as 6012Cumec	21.44% ; @0.34% / year	Volume as 5975, 5868, and 5890 cumecs during the period 2010-2020, 2013-2017, 2017-2021	The present study with av. an error of 2.25%

The present study reveals as follows:

1. In the initial 25-30years, there was heavy scouring in the reservoir bed indicating continuous and uninterrupted flow through the reservoir. The designed provisions for the utility of the reservoir were ok. The part of sediment/ trashes flows out to the reservoir banks and is deposited there. Less sedimentation and reservoir volume loss were less. Profuse leakage in the galleries.
2. In the second analysis i.e., years 2000-2010, the amount of sedimentation is high and almost the entire reservoir has experienced heavy siltation indicating some irregularities in the flow of water in the reservoir. Rising of reservoir bed and changing the course of water and riverbed observed.
3. During the years 2010-2020, the rate of sedimentation decreased gradually as if the reservoir has maintained its flow regime. The dead storage zones have been reduced (except the zone of action of the silt excluders). The construction of small dams and barrages upstream of the reservoir has trapped a lion's share of sediments, which can be the main reason for the reduction of the rate of suspended sediments.
4. Various studies made in past are in Table 9.

Global scenario

Globally ≈1% to 0.5% of the total storage volume of 6800Cum of water stockpiled in artificial lakes around the world is depleted every year by sedimentation [54]. Consequently, the global per capita reservoir storage rapidly decreased with the peak during the 1980s matching the golden spike period of the Anthropocene epoch [55]. Forfeiture of water storage is falling flexibility in power generation, irrigation, and other utilities.

Sediment impact on power generation

As per the U.S. Bureau of Reclamation's design manual for small dams, the versatility of deposit loading, the mud behaves as a non-Newtonian fluid with an implied pressure coefficient that may cause surface waves. Sediments may block silt excluders or low-level outlets designed to bypass/spill sediment. At times the reservoir behaves as a delta-type valley where flow channels within the reservoir bed take a meandering course such that all the sediment carried by floods gets deposited within the reservoir deviating from the spilling route. Sediment can damage or clog the turbines and other mechanical equipment. Corrosion may lead to surface irregularities, cause material damage, and can lead to extended shutdown time for maintenance.

Sediment impact on the downstream

Dams cause a paucity of sediment downstream flood plain and delta influencing the flora and fauna, as they are sensitive to alteration of both the sediment supply and flow regime. Higher sediment concentration increases turbidity which decreases plant productivity, negatively influencing aquatic and avifaunal species. Sediments released because of sediment management or a dam breach may have environmental effects that can persist for decades.

Sediment management solutions

Sedimentation is the process of the flow of clay, silt, sand, pebbles, crushed rocks, and debris with runoff that moves into artificial lakes behind dams and accrues on the bed of the reservoir. The level of sedimentation depends upon the geology of the basin. various sedimentation reduction methodologies adopted are reducing the yield of sediment from upstream, routing sediment, and eliminating or reallocating the accrued sediment. Structural sediment management strategies of reservoirs are sediment bypassing through sediment tunneling or off-channel reservoir storing, sediment sluicing, drawdown flushing (free flow or under pressure), turbidity current venting, or by mechanically removing after dredging by changing the dam operation rules, [56], [57], [58].

Climate change

Water resources have a pivotal role in agriculture, hydropower, livestock, forestry, water supply, recreational and navigation activities, etc. The climate, rainfall, evapotranspiration, sediment influx, and many others change the hydrological parameters and significantly affect the water resource's sustainability. Climate change (CC) is recognized as the pivotal cause behind the diminishing water resources availability vis-à-vis changed hydrological regime [59], [60], [61], [62].

Rainfall diminution

The Intergovernmental Panel on Climate Change [63] concluded as global warming since the mid-twentieth century in inviting the Anthropocene epoch. The temperature changes have influenced the rainfall pattern which has a direct impact on hydrology, land and water resources, agricultural practices, and finally on ecosystems. The recent changes in the rainfall pattern and extreme events have had devastating effects on water resource availability. The important issue, demands a through and careful study.

Proposal two additional sluices

The failure of the integrated operation procedure, of the four major dams constructed in the upper reaches, and erratic rainfall in the upper basin, the PMF has been estimated by WR Dept, Odisha shall be 69632 cumec which is 27182 beyond the design flood estimated prior. To negotiate the additional discharge DRIP has proposed to encroach 1.0m from the existing free board and fix FRL at 192.02m to 193.02m. Routing of the excess 27182cumec flood, two additional spillways are proposed by the Government of Odisha (one in Rt. Bank near Jhaunjhar Nallah and the other adjacent to Gandhi Hillock in the left embankment, considering the left side spillway as a priority.

Fixing new rule curve:

The rule curve prescribed in1957, needs a fresh rule curve by fixing a new zero elevation at present due to sedimentation and loss of Reservoir capacity. The faulty operation was observed during a heavy historical flood on 18th Sept 2008 like the flood caused due to the Ukai dam across the Tapi River in 2006 [64], [65], [66].

Conclusion

Reservoirs have numerous resolutions, like Irrigation, water supply, hydropower, and flood moderation. Sustainable hydropower is an important issue associated with reservoir sedimentation. The reports of accruing processes of sediment since its inception in 1957 have posed threats to the Hirakud reservoirs. Sedimentation depleted the reservoir storage capacity, and energy generation, thwarting the safety of the dam. Mis-management of the basin invites a negative influence on the environment. The rate of sedimentation decreases gradually with its age. It is important to plan and introduce among various methodologies adopted throughout the globe to deplete sedimentation are bypassing, flushing, sluicing and draw down routing, mechanical dredging associated safe disposal, erosion control by catchment treatment plans and few hydraulic structures upstream to trap sediment and save the dam along with proper documentation. The absence of environmental Impact assessment, sediment balance studies, and design provision of industrial water supply put the reservoir to sedimentation adversities. By evaluating e-flows, implementing recommendations of EIA studies, Reservoir, and basin management studies should be mandatory.

Future Scope: Present study reveals the amount of sedimentation that has occurred since the impounding. If the process continues, the reservoir may be depleted to cater to its benefits and become defunct in near future. It is high time to estimate the rate of sedimentation in the future and take pertinent action so that the reservoir should live long.

Conflict of Interest: There is no Conflict of interest between authors.

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