Sedimentation in East Coast Hilly Terrain Reservoirs; Balimela, Odisha

Abstract:

Globally reservoirs behind dams are changing their hydrologic cycle under a shifting climate. Sediment, the flagship for water resources projects provide negative impact on environment and dam benefits. Sedimentation behind dams is continuous, regular through sequential paths that comprises of erosion, entrainment, transference from upper basin and deposition within the reservoirs. Present study envisages the morphometric study of the Balimela Reservoir active from 1972. The downloading of GIS/RS data from LANDSATS and making Stream order, Contour, slope and aspect maps by constructing Digital Elevation Model using the various ARC GIS tools. The average bifurcation ratio is safe.. Considering the water-spread areas at various elevations of the years 2000, 2002, 2013, 2016, 2019 and 2022, the sediment deposits and reduction of storage volume by 29.945% by Jan 2022 since first impounding. The dam housed in hilly terrains, so there is less increase of catchment erosion except deforestation. The water from the dam optimally used by both the states Odisha and Andhra Pradesh. Preparation and strict adherence of concrete reservoir operation rule, upstream proper upstream maintenance and best catchment treatment plans shall increase the dam's longevity and utilities.

Key words: Balimela, Reservoir,

Introduction:

Globally all reservoirs shaped by damming natural flow confronted by depletion of its utilized volume in later stages impact the reservoir storage capacity at various rates and reduces its paybacks. The 20th century dams constructed without environmental assessment studies that impair the natural sedimentary flow that weaken the delta building processes and deplete the reservoir function in long run (Strand et al, 1982[1], Syvitski et al., 2011[2], Mishra et al., 2017[3], Sumi et l., 2018[4], Sethi et al., 2020[5], Lee et al., 2022[6]),

Principal characteristics associated with the reservoirs behind a dam are the geomorphology, hydrology and hydrogeology of the upper basin, and limnology, geology of the area. The soil attrition, drive and deposition are natural hydrological methods, but accelerated under degraded environment, under poor conservation strategies, land use and land cover changes, anthropogenic stresses, etc. Loss of life storage, depletion in dam benefits, breech/overtopping and finally affecting the downstream highly populous delta. The sustained benefits are irrigation, water supply, flood control, land paybacks, electricity energy, recreational, transportation, ecological Temporal and geospatial sediment studies is pertinent to access the life span of all the reservoirs in the state, (Navas et. al., 2009[7], Dutta et al, 2016[8], Bilal et al., 2017[9], Dorber et al., 2020[10]). Hirakud reservoir is first (out of six) reservoirs in Odisha constructed during 1950's, followed by the Balimela interstate project serving both Odisha and Andhra Pradesh of 1970's.

The soil erosion, drive and deposition are part of natural hydrological processes. The sediment deposit rate accelerate by environmental degradation, lack of conservation measures, land use changes, deforestation etc. Average annual rates of sedimentation of various rivers are different **(Fig 1).** The ayacut area is the source for support for irrigation projects. Due to reduction of useful storages by sediment deposits reduces life of reservoirs. The sediment entry is through bed, suspended, and wash load. The quantum of entry depends upon erosivity, sediment yield/delivery ratio and trap efficiency and quality of sediment. They are the functions of rainfall, runoff, vegetation, LU/LC, lithology and size of the upper basin.

GIS tool with remote sensing is the efficient tool to estimate the rate sediment deposit in various sectors of the water body. The stream order, the slope, the aspect ratio and the water spread area determine the spatial accrue of sediment. Therefore, reservoir sedimentation surveys are indispensable to observe and record more realistic data/estimate to assess the rate of siltation particularly when the reservoir is aged, Iradukunda et al., 2021[11].

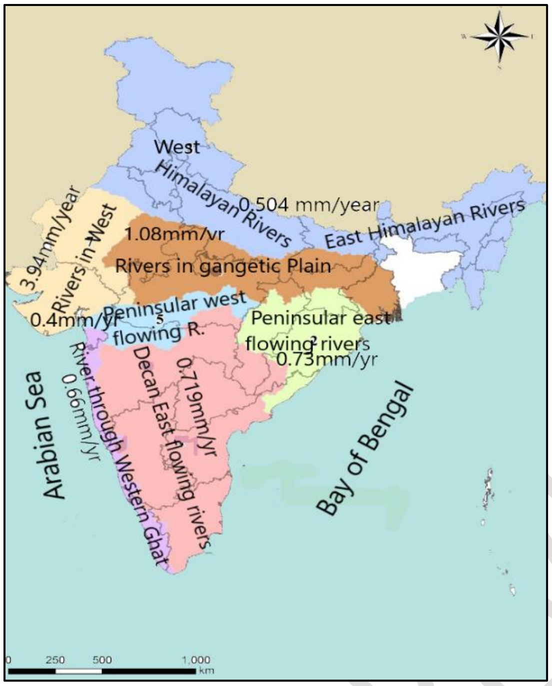


Fig 1: Average annual rate of sedimentation various rivers India (Source: CWC data)

Review of literature:

Globally reservoir sediment entry reports soil erosion; transportation and trapping that cause loss of annual live storage @ 0.5-1.0% (60-120Km^3 in 20th century) providing it the life span 50 to 200years, Dargahi 2012[12], Schleiss 2013[13]; Dutta et al., 2016[8], Obialor et al., 2019[14]. For sustained erosion control there is need for land use (LU) changes, judicious management practices and hike in reservoir capacity, Ayele et al 2021[15]. Sediment related problems are complex and associated with storage capacity reduction, curtailment of benefits and downstream threats. Amelioration by sediment influx control, sediment removal by routing, sediment posting and ab-initio provision of large storage volume is possible, Morish et al., 1998[16]. Reservoir's sediment control methods include stochastic/mathematical modeling, bathymetric surveys, Remote sensing (RS) methods, log core studies, LU/LC changes, and multi-frequency acoustic analysis, Dargahi, 2012[17], Rahmani et al., 2018[18], Maina et al., 2019[19], Shrestha et al 2021[20].

RS/ GIS methodologies delivers fast but approximately correct spatial changes of lacustrine areas to estimate considering spectral and geospatial attributes Jain *et al. 2002*[21], Kiruthika *et al*. 2011[22], Gouda et al, 2015[23], Singh et al., 2021[24]. Digital elevation models (DEMs) are important depiction of GIS/or RS (remote sensing) data used in hydraulic, hydrologic, climate change (CC), watershed supervision, and water resources development (WRD) projects (Ali et al., 2015[25], Guiamel et al., 2020[26], Tesema et al., 2021[27]).

Study Area:

The Balimela Reservoir is behind the dam at Chitrakonda powerhouse on the Sileru River that rises from Eastern Ghats belt hills (EGB) range situated, Malkanagiri District of Odisha. The Sileru R. debouches in the River Sabari in Chhattisgarh (tributary of Godavari R). The Balimela dam (18^{0}-08’-25” N lat. and long. 820-07’-22” E), constructed (1962-1977) is an interstate project where the beneficiaries are the states Odisha and the AP (50:50 share), of India (**Fig 1**). The dam is 70m high and is having gross storage capacity of 3610 MCum**.** The live storage capacity of 2676MCum has been designed for generation of hydroelectric power of 510MW (installed capacity) with 135MW as Odisha share. The ≈59.43 cumec water transported by a 2 km long open channel to Surlikonda Barrage and later, irrigation potential of 90.17Tha generated through Potteru Irrigation Project (PIP) to cater the needs of Malkanagiri valley areas. The maximum outflow routed can be 13981.13 m^3/s at MWL 464.76 m, O&M, CCE, PIP, GoO 2020[28].

Fig 2: Balimela Power House and Chitrakonda dam on the Sileru River; Odisha

The AP's share diverted and feed the Upper Sileru dam & PH at Guntuwada by a separate sluice.

The salient features of the dam and the reservoir given in **Table 1 and Fig 2**

Table 1: The salient features of Balimela reservoir and Dam benefits in Odisha.

#	Project Factors	Information	#	Project Features	Information
1	State/District	Odisha/Malkangiri	2	Geo-Coordinates	18^0 08' 25"N Lat ; $82^0$07' 22"E, Long
3	Type/Design flood	Earth fill/14300Mm^3	4	Length/width	1821m/9.15m
5	Max Height (MSL)	37m	6	Catchment Area	4910 km^2
7	Mean annual R/F	1977mm	8	Design flood inflow	36750Mcum
9	Gross Storage Capa.	3610 Mm^3	10	Live Storage Capacity	2676.00 Mm^3
10	Length Dykes I; II,III	853,613, 812m	11	Housed in 4-saddles	10930m^3 /s (10bays)
12	Sluice outlets (2nos)	2x2.44 x3.66m	13	Sluice Emerg. Gate	2Nox 4.90 x 5.40 m
14	AP Tunnel	Circular 7.62m.ø	15	Odisha Tunnel	7.62m.
16	AP Tunnel dis. Capa.	383 m^3/s	17	Odisha Tun, dish.	383 m^3/s
18	AP Installed capacity	375MW	19	Odisha Installed cap.	135MW
Abb: R/F: Rainfall; AP: Andhra Pradesh; Capa: Capacity; Emerg: emergency, dis: discharge; MW: megawatt					

Source: OHPC site Salient features (http://www.ohpcltd.com/Hirakud) [11], GOO, Rathore et al., (2006) [29], Tobgay et al 2014[30]

Necessity for study:

The 50 years old reservoir has provided in interrupted service to AP and Odisha. The sedimentation survey conducted after 27years through hydrographic survey and later by remote sensing survey in 2003 by Central water commission (CWC), India. Since the river housed in hilly areas, the intensity of precipitation and velocity of flow plays important role in the spillway discharge. The reservoir operation Rule curve tentatively fixed as n 31 August as 461.78 m, 30 Sept as 461.93 m and 31 Oct of the year as 462.08 m (FRL). The results are in **Table-2**.

Table 2: The status of sedimentation observed by CWC after first impounding in 1972

State	*Name of Reservoir*	*Upper Basin Area*	*1st Impounding*	*Last survey*	*Initial live storage*	*Total loss live storage*	*loss live storage*
		Sqkm	Year	Year	MCM	MCM	%
Odisha/	Balimela (Sileru R.)	**4908**	1972	1999	**3610**	282.5	7.83
Live storage 1999 HS/(CWC)	*Live storage 2003 (CWC RS survey)*	*Loss live storage (1999)*	*Loss of dead storage up to 1999*	*Annual loss Gross storage*	*Rate of silting*	*Average rate of silting*	*Dead storage*
MCum	MCum	%	%		Th.cum /sqkm/yr.	Th. cum /sqkm/yr.	MCum
2536.56	*2682.17*	5.21	15.32	0.29	10.46	2.13	**934**

The Balimela reservoir is in Juvenile stage as the live storage capacity is not deteriorating and the average rate of sedimentation is less. Hydraulic structures are under construction/renovation. Continuous urbanization, deforestation, and anthropogenic pressure shall accelerate erosion of the upper basin that warrants monitoring of sedimentation of Balimela reservoir (**Fig 3**).

Life Span of Reservoirs:

After impounding of any reservoir, sediment carried from the upper reaches deposited in the dead storage and live storage zone. The size of the dead storage zone decides the life span of the reservoir and in average considered in India as 100years. The designed life span of the reservoir undergoes five stages (Stage I to Stage V) as per Central Water Commission, India.

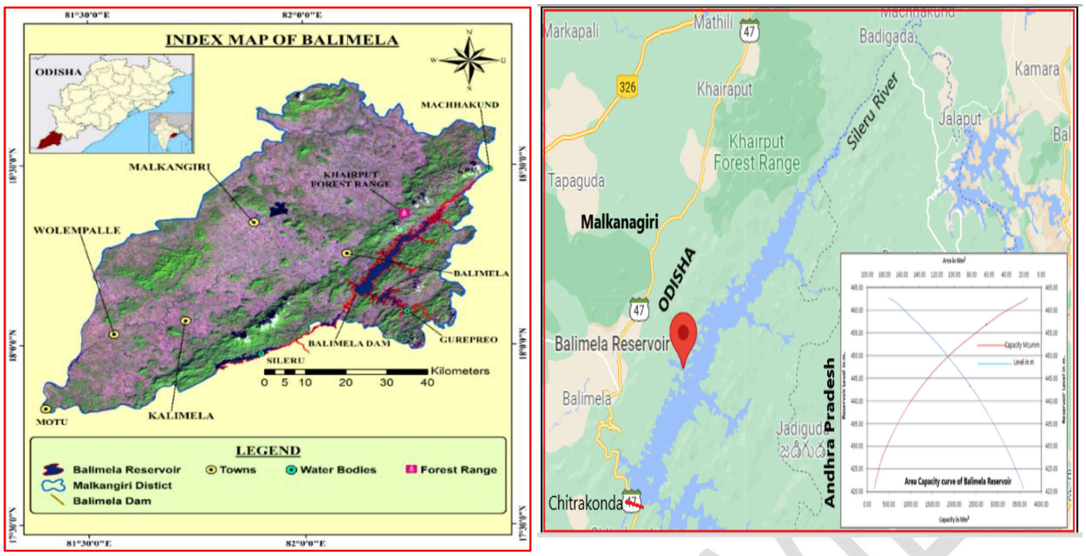


Fig 3: The index map/ Area capacity curve of Balimela reservoir at, Malkanagiri, Odisha

Condition of stage I, have proposition of full life period with all designed benefit, whereas stage II reservoirs provides less benefits and retains the life span. Difficulties starts on reaching the reservoir stage III by hindering the generation and provide adequate water for irrigation and need immediate repair and renovation and desilting. The IVth and Vth stage as completely uneconomical, demands closure of the project by fixing new zero elevation building fresh reservoir curves and building different operation rule or bring innovations by renovating the old dilapidated structures. In Vth stage, (not achieved yet by any reservoir in India) the reservoir needs closure and construction of a new dam at other suitable sites is the best choice, Jacobson 1997[31], compendium, CWC -2020[32].

Sediment quantity Assessment:

Sediment assessment of reservoirs conducted by conventional Bathymetric survey, observational methods (stream flow and capacity survey at regular interval) after few years of operation. Inflows vs. outflows, water depths measured along with concentration of sediment and finally converted to volumetric terms (Butt et al., 2011[33], Güvel, et al., 2021[34]). The modernized methods are in use like buoys, new surveying instruments, techniques and electronic ecosounders etc. The process is time taking, more skilled employment and cost involvement. Robotic boat (buoy) surveys conducted at present using GPS, Remote Sensing (RS) drones or taking GNSS system and DGPS with SD card. This method is working to estimate sedimentation of Hirakud reservoir at present. RS methodology (without physical contact), uses satellites data like, LIDAR, LANDSAT, SPOT and IRS data used for mapping/ monitoring the water surface area. Reservoir sedimentation estimation based on various passes of satellites at different similar time of the year, Jain et al., 2011[35], Jawak et al. 2015[36]; Uma Rajeswari et al., 2018[37], Pratomo et al 2019[38],

Methodology:

Direct computation of reservoir sedimentation is not possible by RS methods. Comparing with ab initio area before impoundment, with present capacity as the observed water spread area of the reservoir the evaluation of sedimentation is possible. Present procedures involves Landsat data from USGS IV and VIII followed by creation of Band Combination Composite Map using the Composite Tool provided in Arc Tool Box under Arc GIS. The unmasking of study area from composite map is the next step. Afterwards the contour map and raster data map from the topographic data created. The interpolation tool used to create IDW map. Exporting all raster files into a separate folder, Raster Files Converted into TIN format. Comparison of TIN Files by use of Surface Tool are the next step after creation of Surface Difference Map (SDM). Later exporting the Attribute Table data of SDM into MS Excel, the sedimentation analysis results obtained.

Present investigation downloading of multispectral images from various Landsat files, and making Digital Elevation Model (DEM). Images received by self-scanning) and Advanced Space-borne Thermal Emission and Reflectance Radiometer (ASTER) are being used for DEM making. The methodology includes GIS and image processing techniques like mosaicking and geo-referencing the raw data from satellite, identifying the reservoir water level, segmentation of waterbody using the pixel level analysis. The water spread area calculated by using water indexing converted in to vector polygon using ArcGIS tools. The transmittance of water significant visible spectrum (0.4-0.7 urn) has the absorption and low reflectance. The contour maps generation is possible by combining GPS and GIS or by two-dimensional model (Aziz et al., 2001[39]).

Table 3: Date wise satellite data used for estimation of various maps of Balimela reservoir

Landsat File Name	Date of Data	Landsat Type
LEDZ_L2SP_142047_20001215_20200917_02.11	15-12-00	Landsat 4-5
LED7_L2SP_142047_20021221_20200916_02_T1	21-12-02	Landsat 7
LCOB_L2SP_142047_20131227_20200912_02_T1	27-12-13	Landsat 8
LCOB L2SP_142047_20161219_20200905_02.TI	19-12-16	Landsat 8
LCOB_L2SP_142047_20191228_20200824_02_T1	28-12-19	Landsat 8
LCOB-L2SP_142047_20220102_20220106_02.11	02-01-22	Landsat 8

Six sets of data sets during December the satellite data used for estimation of various maps of Balimela reservoir like stream order, contour, slope, aspect and the amount of sedimentation.

Stream Order

According to the Strahler (1957)[40], in river morphology the stream order maps presents an organized systematic draw of a river network with proper sizing and classify stream segments and labelling with comparison of stream type, Scheidegger 1968[41]. Stream order found in the big river like Amazon with order 12, and the Mississippi, USA has order 10. Streams (gulley's and brooks) are 1st order (with no tributaries) /2nd order (with tributaries of 1st stream order) have higher gradient, flow straight down the slope with least meandering, as cascaded pools in the mountainous range. With less slope the stream widens, and are third order streams have some meandering, Tarboton 1991[42], Mishra S. P. 2021[43]). The GIS methodology uses Lines (vectors) to signify the number of gulley's /streams or rivers joined at the nodes. Using tools available in ArcGIS, varying of the line width or color to indicate the different stream orders (**Fig 4**).

The stream order map of Balimela reservoir informs 114 numbers of 1st order braided gullies, (not prominent in the map due to steep gradients in hilly areas), 2nd order streams are 31 and 3rd order are 17numbers only. Since numbers of first order streams are high, the water of the reservoir is least polluted, housed in the gorge of two mountainous ranges, Briney Amanda, 2020[44].

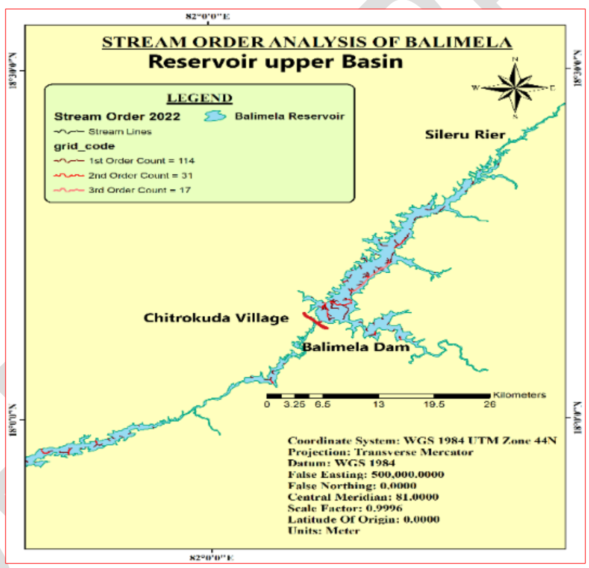


Fig 4: Stream order map of the Balimela reservoir

The high bifurcation ratio, ranging between 2 and 4 indicate that the geologic formations of the reservoir area have not been affected by distortion of the drainage pattern, Khan et al., 2013[45].

Table 4: The Bifurcation ratio of various streams of different stream order

Stream order (u)	Number of stream segment	Percentage composition of stream orders (%)	Bifurcation Ratio (Rb)
1	114	70.37	
2	31	19.14	3.67
3	17	10.49	1.82
Total	162	100	Average= 2.745

The average bifurcation ratio calculated to be 2.745 (lies between 2-4) that indicates the geologic formations of Balimela reservoir area is less affected by distortion of the drainage pattern.

Contour maps

The contour lines are transverse lines of equal elevation above MSL and the space between two consecutive contours tells about the slope of the terrain.

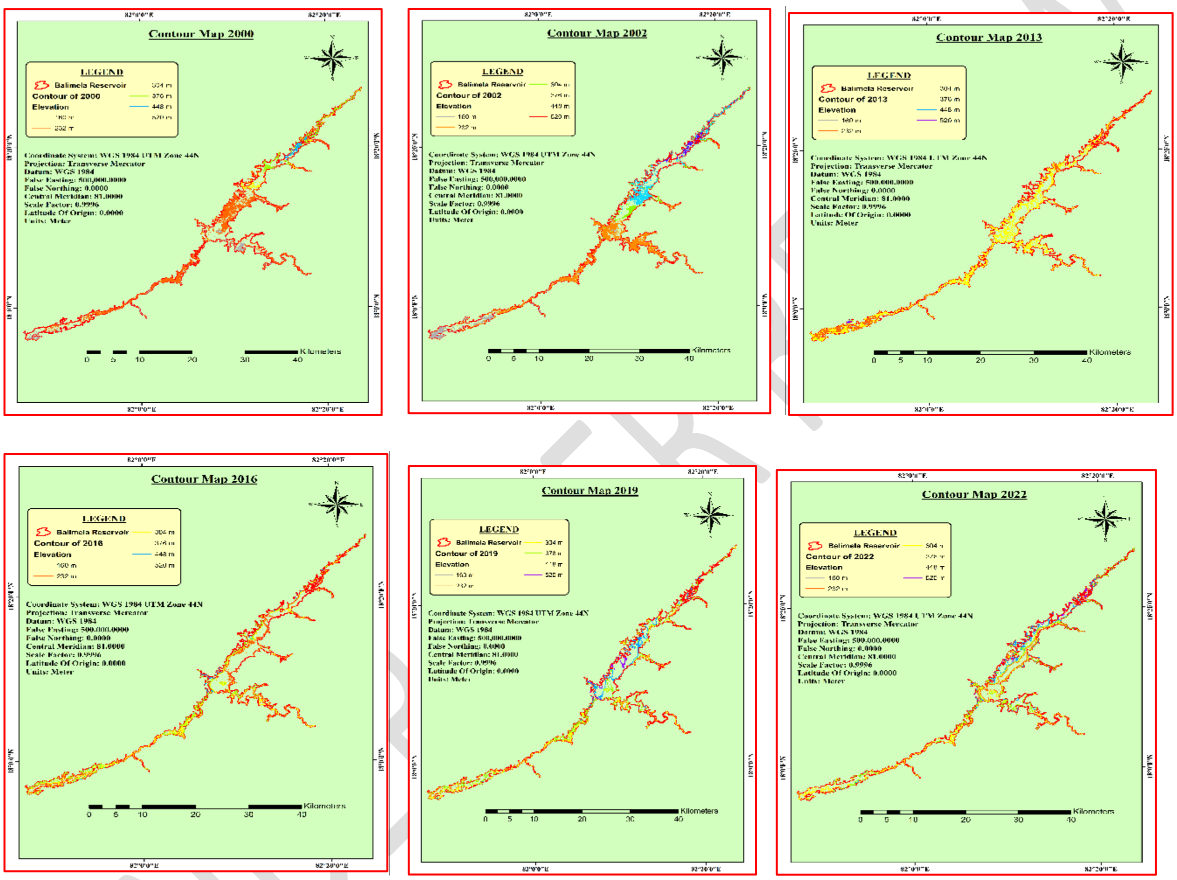


Fig 5(a-f): The Contour maps of Balimela Reser. (Year 2000, 2002, 2013, 2016, 2019 & 2022).

The contour lines are well representative of relief features of a reservoir. The contour map made for a reservoir utilized to know about nature of the ground variability, route of fluvial flow, and distance between observing stations, estimate the storage capacity of a reservoir and its upper basin catchment area (Mishra et al 2021[46]).

Least significant changes observed from 2000 to 2022 on the overall contour lines of Balimela reservoir areas, **Fig 5(a-f).** However, some changes in contour lines noted between the years 2000 and 2002.

Slope maps:

The coarse sediment architecture in a reservoir received from riverine flow material that forms bars, channel bed and often deposited in the banks whereas fines near the toe of the dam or in the dead storage zone (Kond0f et al., 2014,).

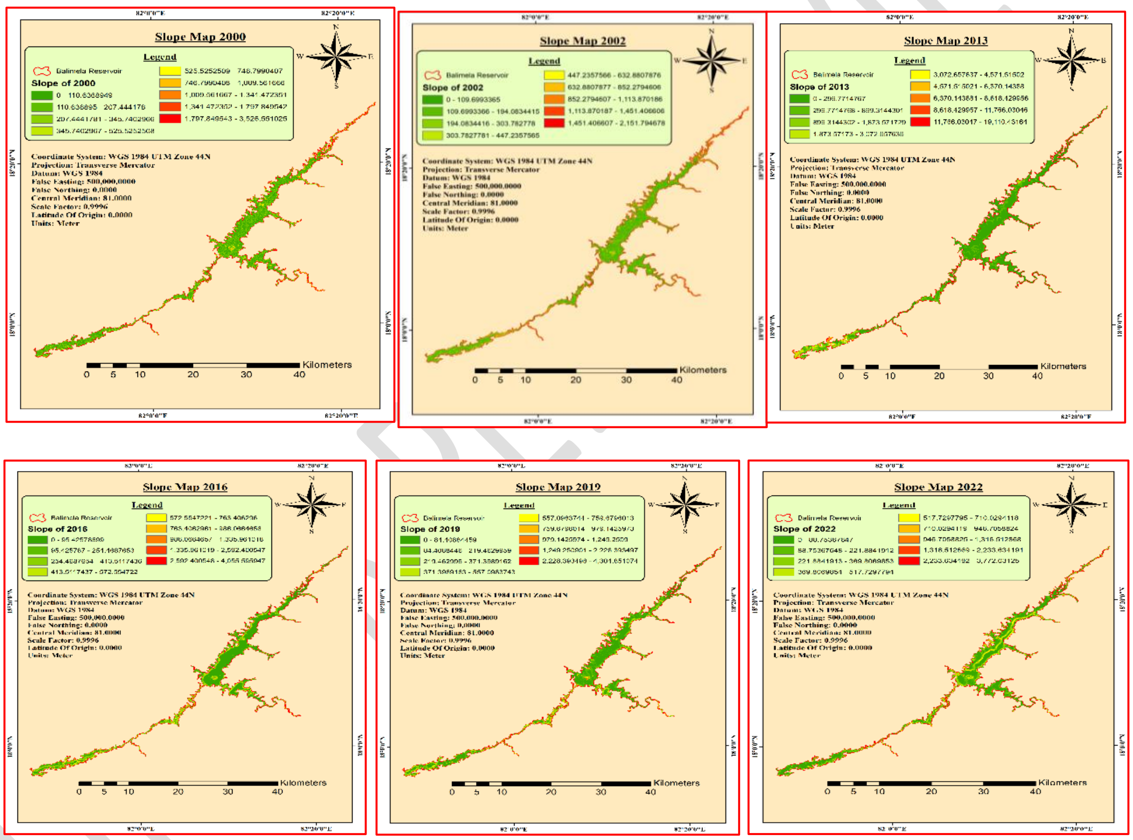


Fig 6(a-f): The slope maps of Balimela Reser. (Year 2000, 2002, 2013, 2016, 2019 & 2022).

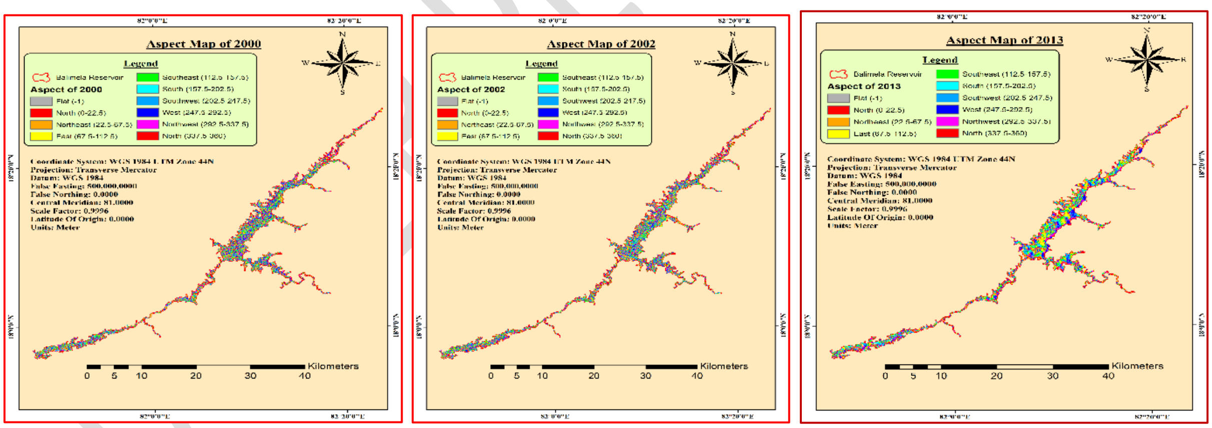
In surface analysis, some raster-based analyses deliver ideas about the ground perceptions of the terrain by the slope maps show the different direction of flow in different colours. The steepness stated by its saturation (steeper slopes as brighter). The erosion from upper basin of a reservoir is computed by USLE method uses slope equation (Browning 1948) as the soil erosion losses varies with factors such as slope steepness (S), conversion (P), slope length (L), rainfall erosivity (R), soil erosivity (K), and cover management (C) given by (Dutta et al., 2016[8])

$$A=RKLSCP \qquad \text{eqn 11}$$

The slope (steepness) map of the reservoir map taken for different 6years (2000, 2002, 2013, 2016, 2019 and 2022) but during the December months when the reservoir has almost same water budget status. From the six slope maps of Balimela reservoir constructed reveals that a channel formed from the entry point to right fringe of the dam gradually, **Fig 6(a-f).**

Aspect map:

In reservoir analysis, the input in RS is a filled DEM where the surface is flat having no undulations. Keeping in mind, the flow direction raster created considering the stream and flow network generated. Slope and aspect maps have real world applications like cropping by farmers, microclimate for the vegetation/biodiversity, and landscape features (ridges/ valleys) etc... Present study focusses on the ridges/valleys and biodiversity upper basin of the Balimela basin.



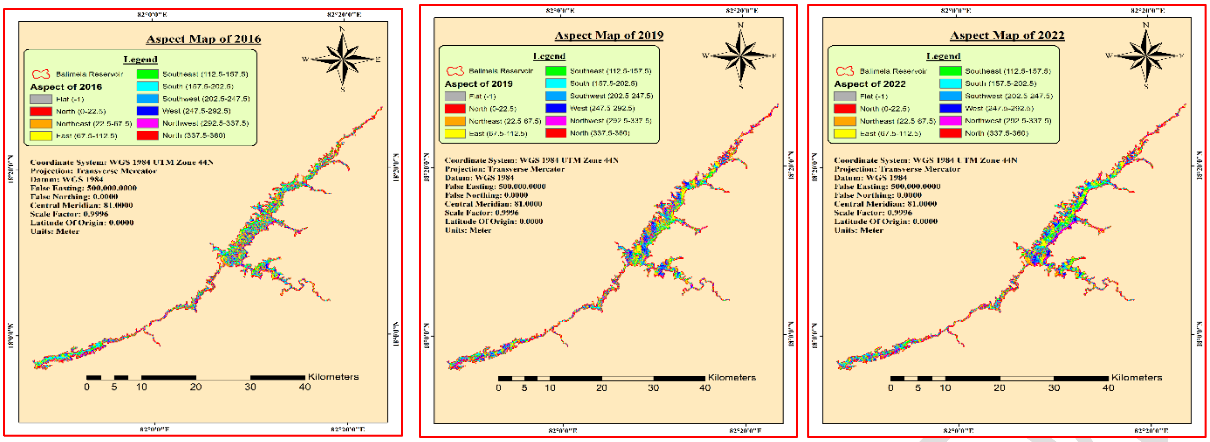


Fig 7(a-f): The Aspect maps of Balimela Reser. (Year 2000, 2002, 2013, 2016, 2019 & 2022).

The cells with large flow accumulation values indicate stream channels, whereas cells having low flow accumulation represent uplands. The aspect map and the values associated specify the directions of the physical surface of the slopes created from free global DEM data sources. The slope and aspect maps prepared to identify the gradient and downslope direction.

From the six years aspect map, there is shift of the aspect (direction) observed. In the year 2000 to 2002, the direction of flow flat whereas, gradual change in direction of major flow shifted to the right fringe of the reservoir.

Sediment Quantity Estimation:

Present case two-dimensional model used where the sediment load (S_L) varies proportionately with time (T in sec), discharge (Q_w Cum) and suspended sediment (S_s kg/cumec) given by

$S_L \propto T$ ..... *eqn* 2 $S_L \propto Q_w$ .... *eqn* 3 *and* $S_L \propto S_s$ *eqn* 4

Combining the above three equations $S_L \propto S_s * Q_w * T$ eqn (5)

The suspended sediment concentration at any cross section (C_{ss}) due to discharge at the control section$(Q_w)_d$, the equation is $C_{ss} = A * Length\ (Q_w)_d + B$ eqn 6

Where A & B are two constants for any section

The sediment volume (V) estimation is possible if the density of deposit of sediment (ρ) at any point given by the equation:

$$\rho = \rho_{min}\,(\rho_{max} - \rho_{min})(1 - e^{-t/\tau}) \qquad \text{………… eqn 7}$$

Where ρ = the density of sediment dumped in time (t). $\rho_{min}\ is$ Initial density at start of sedimentation, ρ_{max} is the final accumulated sediments density, and τ is the characteristic consolidation time as fixed during design. Calculation of volume (V Cum) over an area (A in m^2) of sediment deposition at a section due to deposited sediment of density (ρ) at certain reach of length (L) given by the equation

$$V = {}^{Q_s}/_{\rho} \quad and \quad A = V/L \qquad \text{…… eqn 8}$$

The deposition of sediment (depth) accepted to occur transverse direction irrespective of contour as the distribution of velocity. The velocity along the longitudinal distance and the transverse distance, w.r.t to time. The velocity $(\vec{v})$, at a sectional distance (x), about any cross section called the longitudinal distance is given by

$$\left(\vec{v}\right) = c_1 + c_2 x_1 + c_3\, x_2 + c_3 \dots \dots \qquad \text{……. eqn 9}$$

Where c_1, c_2, c_3 , … etc are constants as functions of time, where $c_1 = A_1 Len\,(T) + B_1$ and A1, B1 are two constants.

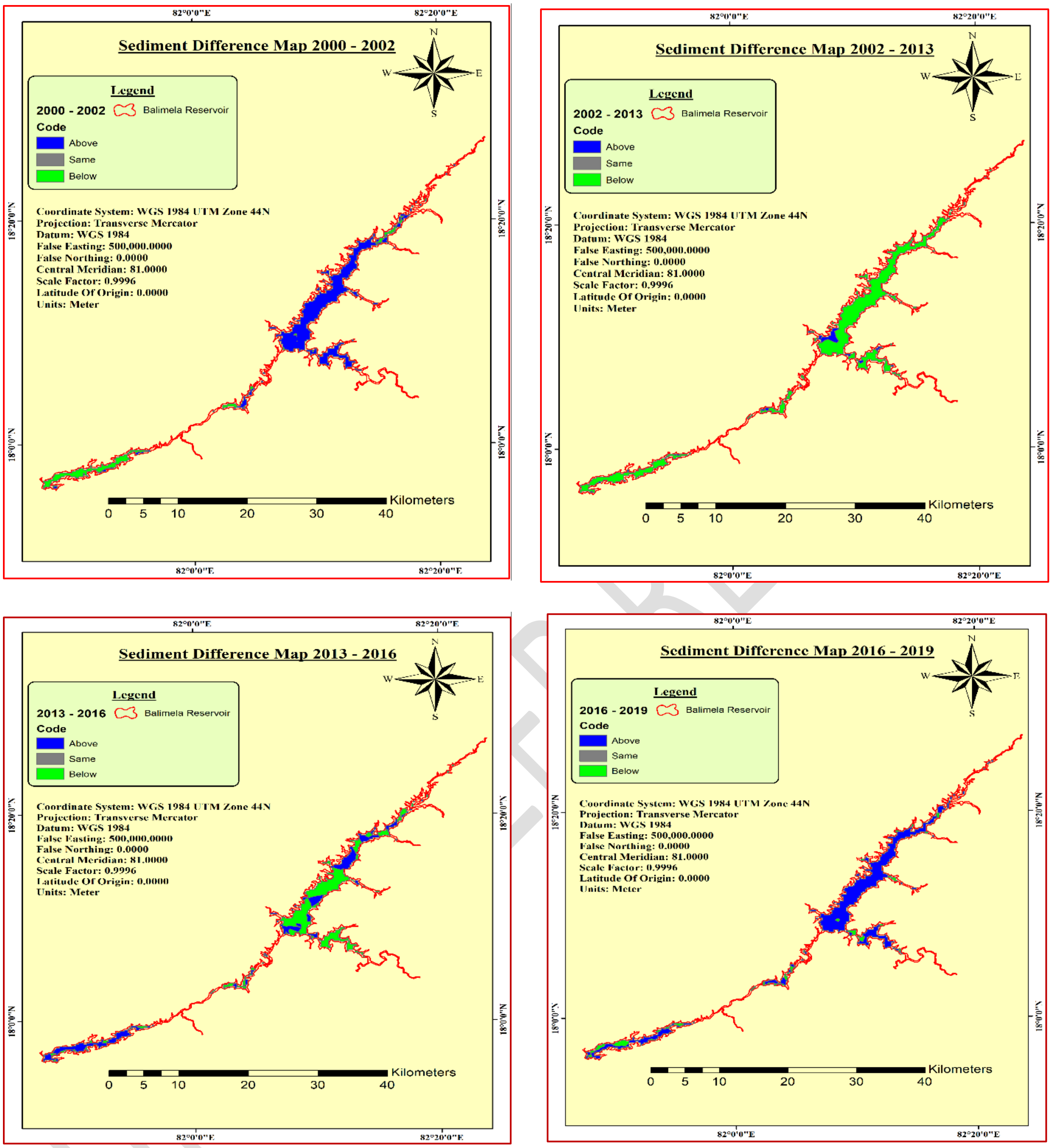


Fig 8 (a-d): Sediment deposition in Balimela Res. (intervals 2000-2002; 2002-2013, 2013-2016)

Calculating area and depth per each pixel, the total water volume calculated based on the empirical model developed using the past-validated data. The cone formulae used to calculate the water volume and given by

$$V = \frac{h}{3}\left(A_1 + A_2 + \sqrt{A_1 A_2}\right) \qquad \text{……… eqn. 10}$$

Where V = Volume of water between two consecutive spreads, and A_1 & A_2 areas between two successive spreads. (Dadoria et al., 2017[47]).

The loss in storage affected by sedimentation since first impoundment and the yearly sediment yield rate can assess the location accrue of silt and bed load, sediment size and densities along with trap efficiency of the reservoir (Rai et al., 2017[48]).

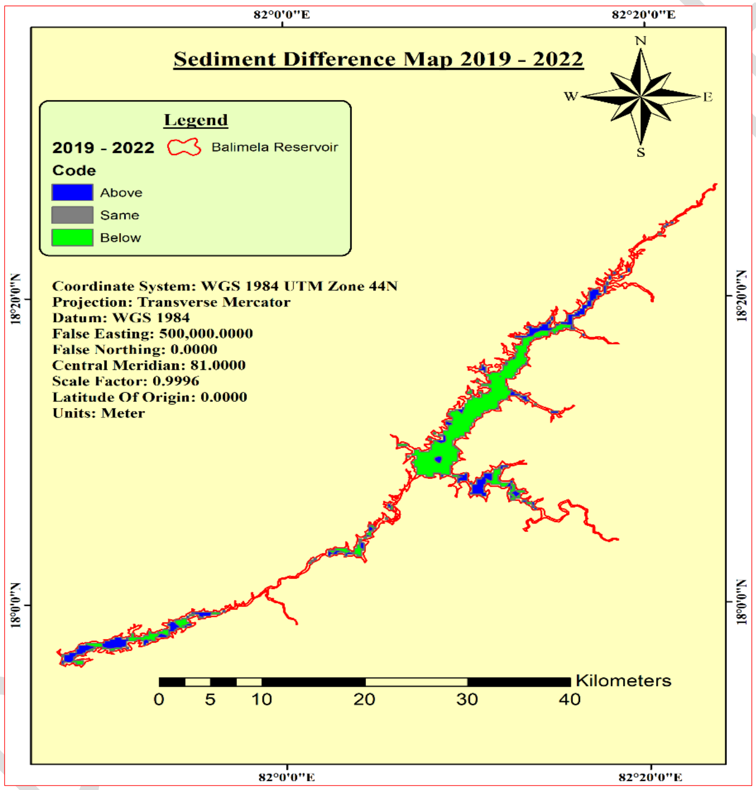


Fig 9: Sediment deposited in Balimela Reservoir from the year 2019-2022

The past floods passed through the reservoir during fag end of October and the dam has spilled 125.35, 590.23, 7689.3, 470 .37 and 964.5 cumec in the year's 1990, 1994, 2006, 2013 and 2018 when the water level in the reservoir were 462.37, 462.23, 462.26, 462.28 and 461.93m respectively (O&M manual, GoO, DOWR, 2020[28]).

Table 5 . Year wise variation in Total Siltation

Reference Year	Volume in MCM	Volume loss (%)	Calculated Catchment Area (km²)	Total Siltation (MCM)	Error % of water spread area
1999	3328.00	0.0	4908.00	NIL	
2000-2002	3261.00	2.01	5209.56	5209.56	6.14
2013-2016	3141.00	5.62	4891.66	4891.66	0.33
2016-2019	2976.00	10.58	4901.98	4901.98	0.12
2019-2022	2529.00	24.01	4974.35	4974.35	1.35 (av =≈2%)

Note: High % of error due to LANDSAT 4-5 data not matched LANDSAT 8 data with acceptable percentage of average error ≈2%

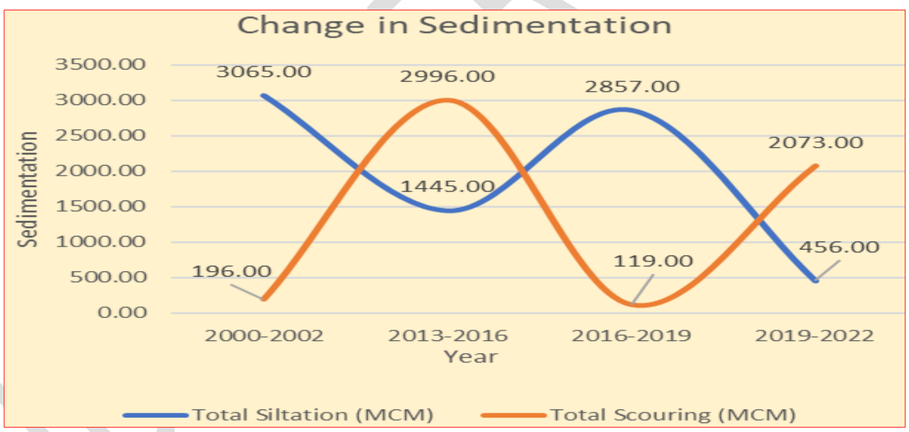


Fig 10: The status of silting and scouring of Balimela reservoir in various by 2000-2022

Table 6: The changes in volume of storage in Balimela reservoir from 2000 to 2022

Years	Initial volume (MCM) (1972)	Volume in MCM	Sediment accrued (in %)
2000-2002	3610	3261.00	9.67%
2013-2016	3610	3141.00	12.99%
2016-2019	3610	2976.00	17.56
2019-2022	3610	2529.00	29.945%

The average annual sediment deposition in Balimela reservoir is 15.44MCM @ 0.4278%

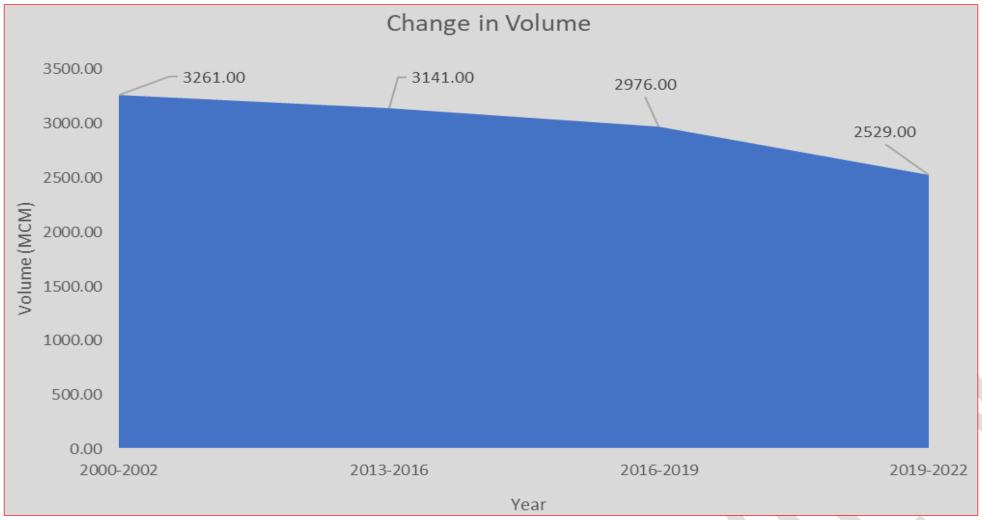


Fig 11: The volume changes due to sedimentation considering base year 2000 as volume 3261cum

Discussion:

The cross sectional area increases reducing surface flow velocity whereas density current prevail under water. The slow but sluggish peripheral sediment trapping process reduces the live storage capacity, loss of energy generation, and affect the delta building process due to shrinking, sinking and subsidence. Proper selection of site, reservoir design, dam construction in stages, check dams, vegetation screens with catchment treatment plans and control/diversion of sediment are the pre-dam strategies need due attention during proposing the dam. Post construction policies are to regulate sediment entry and deposition in diverse segments of the body of reservoir, provision of Saxophone Sediment Sluices (SSS), removal of post floodwater, continuous mechanical agitation/ drawdown flushing to keep sediment in suspension and removal by under sluices. The erosion control through check dams and vegetation cover in the upper basin along with regular monitoring of sediment status of a reservoir can enhance longevity of reservoirs, Kondolf et al., 2014[49], Pandey et al., 2016[50].

The sediment yield to the reservoir depend upon the characteristics of a river basin that accumulates in the reservoir. They are dependent upon precipitation in the upper basin, surface runoff from drainage channels, the vegetative cover, lithology and easy erodible mountainous rocks, type of soils, Land use and Land cover, slope (creases sediment entry), size of upper basin (increases if basin is small). Watershed control for less supply of sediment depends upon land use, soil conservation, inflow control, sediment diversion, vegetation, sediment-retarding structures, and check dams in its inflow drainage network.

Possible sediment control measures against entry to Balimela reservoir are catchment treatment plan, existing vegetation protection with afforestation, possible check dams, upstream Off-channel reservoirs, deposition control, efficient rule curve for reservoir operation, in time Sluicing/Flushing, and inclusive dredging, White 2000[51], Panda et al., 2020[52].

According to CWC, the rate of sedimentation and annual percentage loss of capacity is 0.95% in gross storages and 0.67% in live storage, observed based on Hydrographic surveys. Similarly for east flowing rivers up to Godavari is (6.8 Ham/100sq.km/year) @0.68 mm/year observed in the east flowing rivers up to Godavari (Compendium Sediment reservoirs, CWC, 2020[18]). In case of Balimela reservoir, the rate of sedimentation for initial 27years was 2.132 Th. Cum/Km^2/year. Present study reveals that the average annual sediment deposition is 4.277 Th. Cum/Km^2/year @ 0.4278% from 1972 to 2022, which is less than the 0.95%.

Conclusion:

From the morphometric study of the reservoir at Balimela across the river Sileru, the following conclusions are drawn:

1. The upper basin of the river Sileru has stream order 4 and the bifurcation ratio is 2.745 indicating the drainage pattern has not disturbed by the reservoir formation.

2. The contour map shows least significant changes of contours during 21st century.
3. From the aspect and slope map, it is pertinent that gradual changes of flow direction has shifted from left to right fringe of the reservoir.
4. The sedimentation since first impounding, the reservoir has lost its volume to a tune of about 29.945%.
5. The average annual sediment deposition in Balimela reservoir is 4.277 Th. Cum/Km^2 /year @ 0.4278%, which is, less than the other east flowing rivers up to Godavari basin.

Though rate of sedimentation is less than the average, but the amount of sedimentation occurred, the basin managers cannot be ignore. It is high time to prepare the reservoir rule curve and stress on removal of the sediments that has already occurred. Further regular sedimentation estimation needed to save the reservoir for future management strategies.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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