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RESEARCH ARTICLE

MANAGEMENT OF THE SEDIMENT TRANSPORTED BY THE SOUTH MAHANADI DELTAIC RIVERS TO THE CHILIKA LAGOON.

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Abstract

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The largest lagoon, the Chilika receives major inland flow and sediment from the Mahanadi River via distributaries, the Daya and the Bhargovi. The lake acts as a balancing reservoir for the south Mahanadi Delta and receives sediment mainly during South West monsoon. The excess sediment load and lithification are the grounds for downsizing and deterioration of eco-health of the lagoon. To maintain hydrodynamics and salinity, a straight channel was dredged at Sipakuda (2000) in the Chilika and the Naraj barrage (2004) was constructed at delta head. Renovation of the Gabakund cut on Bhargovi left embankment (2007) is diverting 50-60% of flood to sea (before reaching the lagoon). Pre and post interventions influence the sediment flow to the lake. Suggestions for maintaining threshold sediment flow to the lagoon by the rivers Daya and Bhargovi were ascertained. The methods used in the investigation are regression analysis and stochastic modeling. It is observed that nonlinear regression with power function and logarithmic 3rd order equation having R^2 value of 0.96 gave the suitable PDF relations. The estimate of Sediment during monsoon by Gumbel II and log Pearson Type III was done where LPT III type estimation was found fitting. The reduction in concentration of sediment flow in the Mahanadi River, drop in country flow to the lagoon due to geriatric River, the Bhargovi and various strategies for controlling sedimentation in the Chilika lagoon are detailed in the study.

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Introduction:-

Deltaic landmass covers 1% of the globe that is enriched with flora, fauna, avifauna and aqua-fauna and accommodates 500 million people. Sinking, shrinking and subsidence of deltas in the coastal land are common. The Dams are capturing 730km^3 sediment of 25GT/year in total deltaic area of one million Km^2 of the earth. (IPCC Report-5, 2014)[1]. Blocking natural flow by large dams, dykes and hydraulic structures plays important role in sediment capture and shrinkage of the delta (Dandekar P., 2014)[2]. The sediment starved flows erode the beds, banks and levees. Breaches are common and cause severe flood in the deltas. Flood inundation, water logging, change in land use and land cover add to deltaic deterioration. (Syvitski J. M. et al, 2012)[3]

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The dams, Hasdeo Bango & Tandula, Sondur, Dudhawa, Ravisankar and Hirakud are retaining 66.6% of sediment of the river Mahanadi. (Gupta et al 2012)[4]. The river Mahanadi discharges 11.8 x 10^6 MT of sediment carried by 49.3Bcum from a drainage area of 124 x 10^3 Km^2 catchment area annually during the study period 2000 to 2010 (Bastia et al., 2016)[5]. The huge loss to the delta of retention of sediments by the Mahanadi delta was not discussed in the conference on 8th Nov. 1945 for the unified development of the Mahanadi valley chaired by CW&NC,(1947)[6]. During EIA studies and cost benefit analysis of the Mahanadi valley project the sediment aspect was ignored but actions were laid down for reservoir sedimentation.

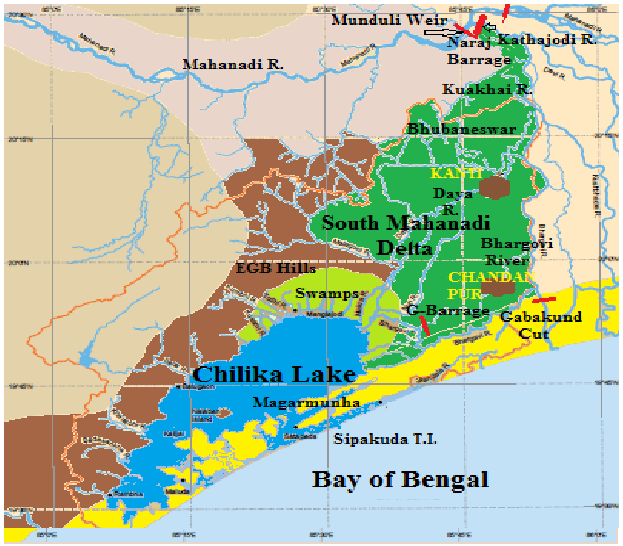

Fig 1:- Index map of south Mahanadi Delta.

Towards fag end of twentieth century (1985-96), the lagoon suffered from acute sedimentation problems, reduction in water spread area from 1165 km² to about 1000 Km² with incessant decrease in salinity from average 17 ppt during 1956 to 4 ppt in 1996 *(Kumar R. et al., 2012)*[7]. ***The average aqua catch drastically reduced from 8000 MT to 1500 MT and the ecology was under jeopardy. Major threats to the lagoon are sedimentation, salinity changes, proliferations ipomeas, water hyacinths and other fresh water weeds and changes in species structure. The anthropogenic perturbations are local shrimp/ prawn cultivation, excess tourism activities, depletion of mangroves, construction of gherry-bundhs around the islands, over-exploitation of bio resources and social, political and economic conflicts. The results are reduction in catches, lake water pollution diminution in lake dimension, circulation / salinity leading to poverty, occupational shift and migration of the stake holders.***

Sediment inflow to the Chilika lagoon (about 70-80%) is mainly through the Daya and the Bhargovi rivers of the south Mahanadi delta (SMD). Towards last part of twentieth century, the lagoon suffered from acute sedimentation problems and reduction in lake size with incessant decrease in salinity. Scientists advocated that the lagoon was at threat of conversion to a sweet water lake similar to the Kolleru Lake in Andhra Pradesh.

Fig 2 a:- Upstream of Naraj barrage during flood **Fig 2 b:-** Dredged tidal inlet at Sipakuda,:the Chilika

Attempt has been made to study the sediment inflow to the lagoon through the Mahanadi system. Management strategies have been chalked out for reduction of sedimentation in the lagoon to provide threshold flushing flow at different flow scenario's in the Mahanadi River. It has been tried to show that the Bhargovi river has become geriatric towards its tail end reducing the threshold flushing flow to the Chilika lagoon.

Review of literature:-

The particle size distribution of sediment of the river Mahanadi in 1947 at Hirakud was 76% fine graded, 13% medium graded and balance, coarse as reported by **Audin J., (1950).[8]** **Delta development Plan 1986[9]** of Govt. of Odisha mentionedthat the Mahanadi River was transporting total sediment load of 29.62 MMT annually into the Bay of Bengal. **Chakrapani et al., 1990[10,]** reported that more than 95 % of the sediment discharge took place during SW monsoon about 90% of sediment discharging directly to Bay of Bengal during flood without settling in the lagoon **Rao Nageswara K, 1993[11] .**The Holocene landform of the SMD is associated with the beach ridges and abandoned distributary channels. They are faint at present as they were washed out by regular floods in the delta. **Ghosh et. al., 2003[12]** reported that Mahanadi System provides 1.5 MMT of sediment annually to the lagoon from the north and 0.3 MMT, from the western sector. **Church M. (2006)[13]** has stated that sea ward propagation of shoreline along east coast causes faulting in the pro-delta slopes and migration of river channels due to movement along these coasts. Church classified alluvial rivers as Labile channel, Threshold channel and Transitional channel. The range of mean sea level rise (MSLR) along Visakhapatnam and Diamond harbor were 2.42mm/year and 4.87 mm / year whereas the global trend is 1-2 mm/year during early 21st century. It is partly due to sea level rise and partly due to land subsidence **Unnikrishnan et al., 2007[14].** SMD basement has Paradip- Cuttack-, and Delang to Konark depressions.. The soil thickness at Puri, Cuttack and Paradip were 2500m, 3000m, 1400m respectively **Nayak G. K. 2006[15].** **Schumm S. A. (1993)[16]** classified alluvial rivers in three categories as Suspended load dominant, Bed load dominant and combined dominance alluvial rivers.

Leopold et. al (1953)[17] proposed that simple power function are suitable to correlate width (B), depth (D) and velocity (V) to discharge Q). Equations are in the form $B = a Q^b$,$d= c Q^f$ and $V = k Q^m$, Latter relations were made for rugosity coefficient (n) and gradient (S) as $n = N Q^p$ and $S = Q^y$ where a, b, c, f, k, m, N, p, S and y are the parameters in the equations respectively. **Chong (1970)[18],** also advocated power functions as suitable for representing regression relation between flow and sediment. **Park 1977[19], Rechards 1976[20]]** stated that power functions are not the best to represent the hydraulic geometry of a stream as depth and velocity are functions of bed roughness. Since bed roughness is ever varying a nonlinear regression shall be suitable. **Glysson G. D., 1987[21]** tried to find relation between suspended sediment and discharge of streams by using power functions and logarthimic functions $Q_{ss} = a Q^b$ and $\text{Log } Q_{ss} = \text{Log } a + b \text{ Log } Q$. Where a and b are constant Q is the discharge in Cumec.

Gray et al 2003[22] found a linear relationship between suspended sediment (Q_{ss}in Tones/day) and discharge (Q cumec) using the equation Qss = Q Cs k where Cs is concentration of Qss in milligrams/liter; and coefficient k =

0.0864 in SI units sp. wt. of sediment = 2.65, He conducted regression analysis between suspended sediments and discharge and opined Log Pearson type III are the suitable for estimation.

Ghosh, D. K et. al., 2011[23] stated that there is 14% decrease in sediment over a decade due to anthropogenic activities. The dissolved load is < 25% of the total sediment. As per **CWC Data book, 2003 to 2016[24]**, average Monsoon sediment load of Mahanadi basin at Tikarpada is 5889.3MT from 1908 to 2003. **Globevnik et al, 2009[25],** stated that anthropogenic activities enhance natural process of erosion and sediment influx to river runoff. But dams cause subsidence in deltas for paucity of available sediment due to retention **Syvitski et al, 2009[26]**. The rate of Soil erosion in the Mahanadi basin fluctuate from 116 to 940 t/km2 /yr. (**Chakrapani 2014**)[27] whereas the erosion rate in the delta is 200 to 400 MT/Km^2. The River Mahanadi discharges average 15.74 MMT of sediments annually to the Bay. **(Mohanty M. 2005)[28].** Calculating from CWC data **Bastia et al 2016[5] reported** that the catchment area of the Mahanadi River at Tikarapada is 124,450 Km^2 and the amount of sediment discharged 17.37 MMT by 49.05 Bcum annually.

Methods and Methodology:-

The Daya and the Bhargovi are monsoon fed ephemeral rivers and good repositories of alluvium since pre Holocene period. To estimate the sediment ingress to the lagoon by the rivers Daya and Bhargovi, two observatories were set up one at Kanti, 18.2 km on river Daya and the other at 48.5km of river at Chandanpur over river Bhargovi. Major sediment (80-90% annual) was found to be transported in the rivers with SW monsoon flow. Daily sediment observations (dissolved, suspended sediment) and annual bed load were taken at both the sites along with gauge and discharge observations. Observations (2000-2004) were taken by the author during study of **hydro-biological monitoring of the Chilika Lake[29]** of Water Resources Department, Odisha. The suspended solid (SS) and the dissolved suspended solid were found in the laboratory. The sediment, carried by River Mahanadi in the upstream of the Naraj barrage was also collected from CWC data.

The time series data is developed and analyzed statistically. The suitable probability density function was taken after finding the best goodness of fit test. Linear and nonlinear suitable regression equations were developed from the time series data. Finally Gumbel and Log Pearson Type III model was adopted to estimate future sediment flow through the rivers at different return periods. For all statistical studies statistical software's used are EXCEL, SPSS, and statistical tools at various steps of analysis and prediction.

River morphology in the SMD:-

The path of runoff through a drainage channel assumes the shortest route from highest altitude to the lowest by erosion of a river. These rivers characteristically consist of alternate pools and shallow reaches connected by straight channels. Braiding in the mountainous reach and meandering with ana-branching in the alluvial reach are their characteristics. The Rivers in shallow reaches are governed by their channel width. The deltaic branches are anastomosed for low hydraulic gradient with respect to base level. In case of the rivers Daya and the Bhargovi, the riffles created during formation get eroded by utilizing part of the energy of flood and erode the bank/levee and become the source of sediment. The sediments are transported either as bed load or wash load (dissolved sediment + suspended sediment). The river cross sections adjust with flood initially by erosion within flow section. But in case of excess flood the flow route is enlarged gradually. The widening of the river is done by meandering, avulsion and ana-branching of the channel in the process of anastomosis.

The SMD Rivers in young landform:-

Present deltas in the east coast of India, began forming during 7,000 years B.P when MSLR became constant just after the little ice age in the Holocene Epoch. The geomorphological exhibits are beach ridges, mudflats, mangrove swamps, lagoons, and spits. The present delta of the river Mahanadi had a number of old river systems within the delta such as the Sukhabhadra, the old Kathajodi, the Burdha, the Alaka, the Prachi and the Ratnachira, which are either defunct or abandoned at present. The present river system is the Birupa-Mahanadi-Kathajodi system (Mahalick et al., 1996)[30]. The reasons for continuous delta formation are the quantity, transport pattern of sediments and marine influence in the estuaries. The strand plains represented by sandy beach ridges near the Ghoradia Village, 35 Km from the Chilika indicate that the coast was near Jatni in past. Similar types of beach ridges are also found in the Godavari delta is 35 Km inland as reported by (Rao K. N. et al., 2012)[31].

Radio carbon Studies:-

The radiocarbon dating data available from various sources corroborates about the age of formation of the rivers in the young SMD Table I.

Table 1:- The carbon dating data results in the south Mahanadi Delta confirming its age (Mishra et al 2015)[32]

Sl No	Name of Channel/water body	Place	Length in km	^{14}C data result in years BP	formation Years BP	Remarks (Formation age)
1	Chilika	South Sector		792 ± 2 Ma		lake anthrosites Study Dobemier C. 2009[33]
2	Kushabhadra	Bhubaneswar	56	1220±180	1220-750	Young, active, 8 to 2.5m high
3	Bhargovi R.	Uttara (Bhubaneswar)	85.5	1590±150 - 1220±180	2300 -750	Old, inactive for last 40kms, 8 to 2.5m high
4	Daya R.	Uttara (Bhubaneswar)	60	2300 -750	2300 -750	Young, active, avulsive 8 to 2.5m high
5	Rajua (a loop branch Daya)	Kanti (Jatni)	16.5	250-0	250-0	Young & active, Makara branch became active
6	Chilika Lake (C Sector)	Near Raghunathpur	West bank	3750±200	3750	A part of Gulf shore, **(Arya R. 2006)[34]**
7	Chilika Lake	19° 43' N, 85.37° E	Satapada	538 ± 5	500	Low lying swamps in N-Sector **(K Dutta 2001)[35]**

The radio carbon data of soil in SMD tells that some formation is hardly 700 to 800 years B.P.. The SMD also have both young and old alluvial plains. The barrier spit in the northern sector near Satapada is hardly 500 years B.P. and that between the outer channel and the lagoon seems to be still younger. Probably the inner channel extending from Satapada existed with mouthing activities prior to formation of present outer channel.

Lithification process in the coastal zone:-

The silt and clay carried as suspended sediment were initially mixed with the fine to medium sand received by the lagoon through tidal inlet and outer channel by horizontal stratification and vertical mixing. The compaction process is initiated in the lower layer to the clay minerals followed by recrystallization of calcareous materials such as $CaCO_3$ and aragonite sand received from marine sources. Then the process of cementation occured where water was driven out from the solid by hardening. Finally by the process of authigenesis, mineral mediation occured to form a solid rock leaving organic solidified layers in between. Sedimentary rocks are found in and around the Chilika growing by lithification.

Palynology studies:-

Palynological studies of 250 m deep Sadanandpur profile in the west bank of Chilika lake was done by **Gupta et al., 1996[36].** According to them Paleo records reveal the sedimentary deposit status and indicate quaternary sediments of the Mahanadi delta with regressive and transgressed species between depths 236 to 250m, 218 to 223m and 170 to 211m confirmed by pollen evidences. They have also found marine marginal shifts within a depth of 53m to 142m and the interstitial zone preponderance with organic deposits. Between 48-50m depth there was sign of fresh/brackish water pollens indicating regression of the Bay of Bengal forming salt marshes. Basing on this litho and palynostratigraphic study they confirmed that the strand line was passing through Delang- Jagatsinghpur-Balasore,

Drainage History:-

As history records, the river Bhargovi was directly debouching to the Bay of Bengal along with its branch, the Sunamunhi near Harachandi temple. The river Bhargovi moved away from the coast leaving behind some shore perpendicular channels (South Kania, Buxi kania etc.) joining the river Sunamunhi and later joined the Daya and finally submerged in the northern swamps of the lagoon. The river Sunamunhi became defunct during last 60-70 years after the dredging of the Mangala cut (1936) in the southern outskirt of Puri.

The Gabakund cut dredged in the left bank of the river Bhargovi during 1963's and its renovation with a pilot channel during 2002-07 diverted 60-65% of flood discharge of the Bhargovi to the Bay of Bengal at 36Km of the river. Renovation of a branch, the Kanchi-Dhaudia-Mangala river link at 46Km made the Bhargovi more geriatric. Now only 25 to 30% of flood flow of Bhargovi is reaching the lake debarring the lagoon from its flushing flow. Consequently the northern swamps are drying up and are being converted to homestead or agricultural land (**Miishra et al 2016**)[37].

The arcuate shaped lacustrine SMD:-

The south Mahanadi delta like the Godavari and the Krishna deltas along the east coast of India, are all arcuate shaped and lacustrine. This delta of alluvium is formed as the river loses its speed vis a vis energy of transport in the NE swamps of the Lagoon in Kanas and Brahmagiri block area. The soil strata have the uppermost layer composed of silt, clay, sand. Grits and gravels are rarely found. The forest areas of Kanas block have relatively coarse deposits and they extend up to the lake. The bottom layer consists of black deposits of fine materials which extends from the beginning of the northern swamps to the lake bed. The lagoon never dries up as the filling of the lagoon is done during SW monsoon by discharges of the inland rivers and the rest period by the tides of Bay of Bengal. The back water propagates to Basantpur which is 15 km upstream of the lake.

Sediment status of the lagoon:-

Sediment transport continues from sea to lagoon through tidal inlets during tides and ebb-tides round the year and hinterland sediment during JASO months. **Chandra Mohan, 1991[38]** had estimated the inflow of sediment from the Bay of Bengal to lagoon to be 1MMT. Various investigators **Pattanaik S. 1998[39]**, **World Bank, 2004[29]** had estimated that annual sediment flow from the Mahanadi system were 1.8 MMT and 2.13 MMT respectively. CDA have observed inland sediment loading of Chilika lagoon from the Mahanadi system is 1MMT.The sediment loading from the south Mahanadi rivers to Chilika lagoon was nearly 1.5MMT and from western catchment, 0.3MMT annually **(Ghosh et al., 2006)[40].**

The bed level of the Chilika lagoon is about 1.5m above mean sea level. The core samples of CWRDM, 2004 reveal that the rate of depletion of the lake had been 3 to 5 times that a century back. The rate of depletion is higher in northern and southern sectors than the central sector. The sedimentation rate in 21st century is 1.4 to 1.8 cm/year in the northern and the southern sector where as average lake area depletion rate is 0.7cm/year assuming zero sediment flushing from the lagoon (**Rajat Kumar et al 2012**)[7].

The concentration of sediment at delta head Naraj was 0.506 gm/lit in 1980 and 0.558 gm/lit in 1981. The historic flood of 1982 increased the sediment to 1.006 gms /lit and more in the years 1983 and 1984. The flow distribution of the bifurcated rivers Daya and Bhargovi was almost 1:1 in the period 1980-1984 (Delta dev. Plan, WR dept. GOO).The average annual bed load was about 9% of the total suspended load in the river Mahanadi. The Daya and the Bhargovi together share 5-6% of total flow of the parent river Mahanadi. Sediment received by the rivers either from their local catchment or from the River Mahanadi flows directly to Chilika as both the banks are embanked before 1960 which was entering the flood plains previously. The lagoon receives 75% of inland sediment from the SMD **(Mishra et al 2015)[41].**

Sediment measurement at upstream of delta head:-

Continuous sediment data is available at Tikarpada from 1993-2012 which is upstream of delta head, Naraj. The observations were taken by CWC, GOI. The Mahanadi flows through a rift gorge named Satkoshia between Naraj and Tikarpada where there is no significant flow contributed by any tributary. The local runoff contribute a very small amount of sediment to the Mahanadi system within the stoney reach. Hence flow and sediment observation taken by CWC has been consdered valid as the sediment concentration of delta head (Fig 3).

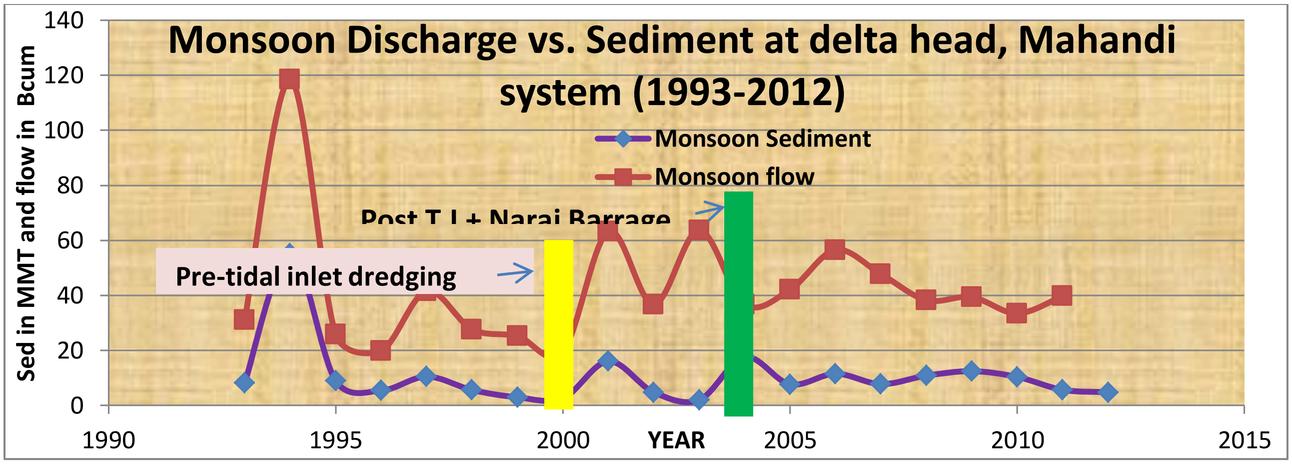

Fig 3:- The time series curve of the discharge and sediment in the U/S of delta head of Mahanadi

Annual discharge vs. sediment flow:-

The annual monsoon flow vs. sediment transport during the years 1993 to 2012 were two parallel curves indicating sediment concentration is having some regression relation with discharge (Fig -3). The sediment flow in 1994 had a very high peak as 4 numbers of floods passed in the river Mahanadi in the year 1994,. The sediment load trend indicates a continuous decrease from 1993as previous data is not available. However it can be ascertained that the Mahanadi basin is becoming old with time (Table 2).

Table 2:- The annual discharge and sediment flow in river Mahanadi at upstream of the delta head.

Year	Moonsoon flow Bcum	Monsoon sed in MMT	Sed conc in gm /lit	Anderson-Darling	Non-Normal at 0.01
1980-81	53.784	27.24	0.50647	A-Squared	1.241054
1981-82	24.588	13.72	0.557996	p	0.00281
1982-83	23.629	23.78	1.00639	95% Critical Value	0.787
1983-84	32.485	29.45	0.906572	99% Critical Value	1.092
1984-85	46.952	47.76	1.017209	Mean	27.38486
1985-86	DNA	DNA	DNA	Mode	#N/A
1986-87	55.319	DNA	DNA	Standard Deviation	21.73887
1987-88	19.814	DNA	DNA	Variance	472.5784
1988-89	21.511	DNA	DNA	Skewedness	1.610515
1989-90	25.379	DNA	DNA	Kurtosis	4.714581
1990-91	65.61	DNA	DNA	n	33
1991-92	40.699	DNA	DNA	Std Err	3.07434
1992-93	42.513	DNA	DNA	Minimum	2.051
1993-94	31.188	8.292	0.265871	1st Quartile	10.43825
1994-95	118.425	55.049	0.464843	Median	24.184
1995-96	25.92	9.042	0.348843	3rd Quartile	42.3735
1996-97	19.87	5.469	0.275239	Maximum	118.425
1997-98	46.232	10.526	0.227678	Range	116.374
1998-99	25.68	5.675	0.220989	Confidence Interval	6.178118
1999-00	25.435	3.031	0.119167	for Mean (Mu)	21.20674
2000-01	16.201	2.658	0.164064	0.95	33.56298
2001-02	57.871	16.098	0.27817		
2002-03	18.385	2.051	0.111558	For Stdev (sigma)	18.15922
2003-04	60.183	17.67	0.293605		27.08953
2004-05	35.644	7.735	0.217007		
2005-06	39.061	11.573	0.29628	for Median	13.72
2006-07	54.486	7.815	0.143431		31.188
2007-08	47.219	10.876	0.230331		

2008-09	49.608	12.497	0.251915	k-Factor Two-sided	-28.6075
2009-10	43.419	10.409	0.239734	0.99	83.37725
2010-11	33.466	5.711	0.170651		
2011-12	39.915	4.837	0.121183	k-Factor One-sided	-22.0056
2012-13	43.193	7.44	0.17225		76.7753

The local mean sea level rise at the confluence points of the rivers has influenced the rise in base level. To maintain the base level **(Schumm 1993)**[16] the channel is accommodating the flow through the changed base level by changing slope or shape or bed roughness at the cost of levee and embankments. The fact is prominent in the Daya and the Bhargovi Rivers which exhibit constant incision in its levee and embankments every year. The final observed time series of flow/ sediment has been prepared for the rivers Daya and the Bhargovi Table 2.

From the data in Table 2 and Table 3, it is inferred that the Naraj barrage upstream and the low level weir at Gabakund have less impact on the sediment concentration of the river Bhargovi. The sediment concentration in a cut or a branch river is less than the trunk one. The average sediment concentration of the river Bhargovi at Chandanpur has increased after the Naraj barrage operation and the Gabakund cut compared to the sediment concentration of the river Daya at Kanti. The concentration of the sediment has decreased from 0.272 gm/lit to 0.236 gm /lit after the interventions.

The discharge and sediment concentration show three phases, the first phase 1980 to 1993-94 where there is high discharge and higher sediment concentration. The 2nd phase of discharge and sediment concentration was 1994 to 2003 when there was reduction in flow and sediment concentration whereas from 2003- 2013 there was rise in annual discharge but reduction in sediment concentration. Similar tendency of discharge and sediment concentration has been shown by yellow river, China (Yu et al 2011)

Table 3:- Sediment delivery to the Lake by Rivers Daya and Bhargovi pre and post Naraj barrage.

Year	Monsoon Month	Dis (Q) Munduli /year	Dis.(Q) Bhargovi / year	Dis.(Q) Daya/ year	Sed-Bhargovi	Sed - Daya	Total Dis(Q) Daya+ Bhar	TSS Daya+Bhar	Sed. Conc. Bhargovi	Sed conc Daya	TSS to Chilika
		Mcumec	Mcumec	Mcumec	MT	MT	MCM	MT	g/lit	mg/lit	mg/lit
	Pre –Sipakuda Mouth										
1999	JASO	32918.4	335.39	1016.79	N.A	N.A.	1352.18				
2000	JASO	10399.14	49.99	194.29	9908	17857	244.28	27765	0.198	0.092	0.114
2001	JASO	79797.51	119.34	2407.49	36616	1028466	2526.83	1065082	0.732	0.427	0.422
2002	JASO	17582.59	78.85	557.35	30749	114133	636.2	144882	0.615	0.205	0.228
2003	JASO	84819.13	105.34	1724.41	27315	626571	1829.75	653886	0.546	0.363	0.357
	Post Naraj barrage							Average	0.523	0.272	0.280
2004	JAS	33781.67	94.69	824.41	46880	255724	919.1	33876.4	0.938	0.310	0.037
2012	JASO	61861.21	83.5	499.62	13690	125552	583.12	61944.7	0.274	0.251	0.106
2013	JASO	60353.28	213.439	1710.06	29192	250239	1923.5	60566.7	0.584	0.146	0.031
								Average	0.599	0.236	0.058

Diminution in area of the lagoon:-

The size of the lagoon and the water spread area depends on the monsoon discharge, tidal influx and efflux, storm impact and anthropogenic activities within the basin and in the catchment of the lagoon. The size and depth of the lagoon has been studied by various authors and agencies in different situations. The accepted dimensions of the lake was 1165 Km^2 during rainy season and 906 Km^2 in summer. However the size of the lake was about 1500 Km^2 and was extending up to Delanga and Golabai (Fig 5). The dimensions of the lake during summer give the accurate information about the lagoon (Table-4) whereas rainy season extensions depend upon the amount of flood absorbed by the lagoon.

Table 4:- Minimum Area of the Chilika Lake Pre and Post Anthropologic interventions.

Month/year	1858	1915	1972	Jan 1973	May 1981	Nov 1985	May 1986	Feb 1993	2000	2001	Jan 2003

Min Area km^2	891	826	824	871	887	863	790	813	790	906*	760
Source	Sterl ing -	Anadale & Kemp	CDA -06	ORS AC	ORS AC	ORS AC	ORS AC	ORS AC	CDA	CDA	AWiFS
Month/ye ar	Jan 2004	Jan 2005	Jan 2006	2007 CD A	2008 Gupt a	2009 CDA	2010 CDA	2011 CDA	2012 CDA	2013 CDA	2015
Min Area in km^2	741	789	764	735	704	754	769	723	742	777	

Lake Depth:-

Thresh hold flushing flood maintains the depth of the lagoon. From history it was found that in the 2^{nd} half of 17^{th}, 18^{th} and 19^{th} century there were a number of dry years in comparison to the 1^{st} half of the century. From 1985-86 to 1996-97, there is continuous irregular silting within the lagoon as no flushing flood passed the lagoon except one medium flood in 1992. This accelerated the sedimentation in the lake up to 2001. Depth of water in the lagoon shows wide spatial and temporal variability. Because of freshwater influx and heavy precipitation during SWM, the water levels in the lagoon are 1m to 1,22m higher as compared to summer. The northern sector is the shallowest region, with depths ranging from 0.2 m to 1.5 m and depth in the central sector (1.5–2.5 m). The central sector has increased depth of maximum 6.0 m after dredging whereas southern sector has depth of 2.5–3.5 m. (CDA Report 2012-13)[43]. The depth of the lagoon varies annually. The flow channels were dredged in 2000 to flush the floods received from the SMD rivers easily.

Table 5: -Maximum and minimum depth (in cm) of Chilika lagoon during summer.

Year	Maximum depth(cm)	Minimum depth(cm)	Av. Salinity	Aqua Catch	source
Pre Naraj barrage			In ppt	(MT)	
1858	488	60			Harrish & Pearson 1858[44]
1988-89	330	50	8.2	6172	Adhikary S et al 1992[45]
1989-90	300	20	7.3	6706	Sahu et al.,2014[46]
1990-91	300	20	7.8	4297	Rajat Ku et al., 2012[7]
1991-92					Rajat Ku et al., 2012[7]
1992-93	340	74	6.0	4173	Ghosh et al. 2003[12]
1993-94	210	65	8.0	3496	Ghosh et al. 2003
1994-95	332	58	11.0	1418	Ghosh et al. 2003
1995-96	382	60	4.2	1274	Ghosh et al. 2003
1996-97	142	42	5.1	1645	Ghosh et al. 2003
1998-99	480	40	4.0	1652	Ghosh et al. 2003
1999-00	330	35	5.9	1746	Ghosh et al. 2003
Post Tidal Inlet (Sipakuda)					
2000-01	677	28	9.3	4983	Ghosh et al. 2003
2001-02	540	31	9.5	11989	Ghosh et al. 2003
2002-03	586	29	14	10894	Ghosh et al. 2003
Post Naraj	barrage				Ghosh et al. 2003
2005-06	420	38	13.4	12225	CDA report
2006-07	350	35	9.8	9956	Panigrahi et al 2009 [47]
2007-08	620	34.7	11	10047	CDA Report
2008-09	682	28	9.3	11935	Jeong et al. 2008[48]
2009-10	550	25	11.2	11955	Mohanty et al 2015[49]
2012-13	620	38		12476	CDR report 2012-13[43]

The combined effect salinity and depth have increased the catch can be ascertained from the table 4.

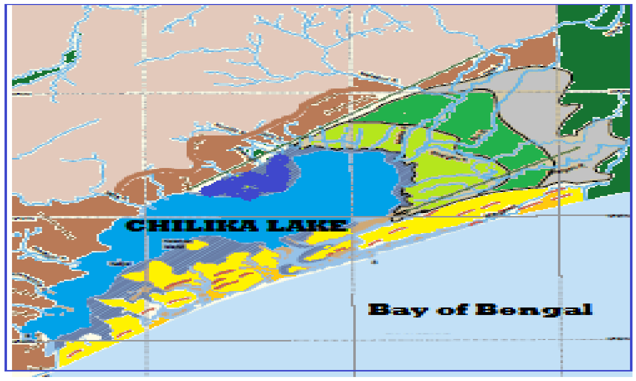

Fig 4:- The greater Chilika, retrospective sedimentation and present status (Sourc e: Rao and Sadakata 1996).

Frequency Analysis:-

Frequency analysis of the time series includes the following steps: (Mishra et al 2015)[52]

1. Verification of hypotheses (homogeneity, stationarity and independence)
2. Detection of outliers
3. Fitting of statistical distributions and parameter estimation
4. Selection of the best distribution to represent the data
5. Prediction of sediment for different return periods.

Time series probability plot:-

The time series plots for both discharge and sediment flow during monsoon flow in the river Mahanadi is proportionate fig 2 . The trend in discharge/sediment is less varying after operation of Narai Barrage Fig 5.

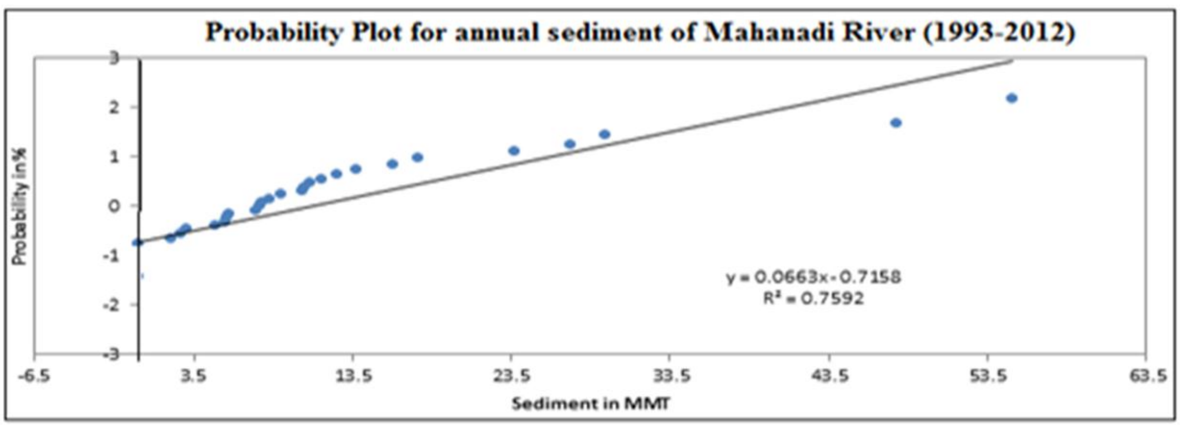

Fig 5:- Probability plot of annual sediment flow through the Mahanadi at U/S of Naraj (1993-2012)

Outliers and general Statistics:-

Outlier in a time series observation is that deviate from other observations than a threshold referred as or related with a specific pattern. In the present sediment data the upper outliers are less significant. The mean, Std. deviation and P-value and others are given in fig 8.While executing regression analysis for the time series data, a data point which deviate largely from the data pattern is an outlier. Sources of outliers may be human error, incorrect reporting or sampling, standardization error etc. By analyzing the scatter plot one can decide the accuracy of the data and assess the error rates (Fig 6 (a) and (b)).

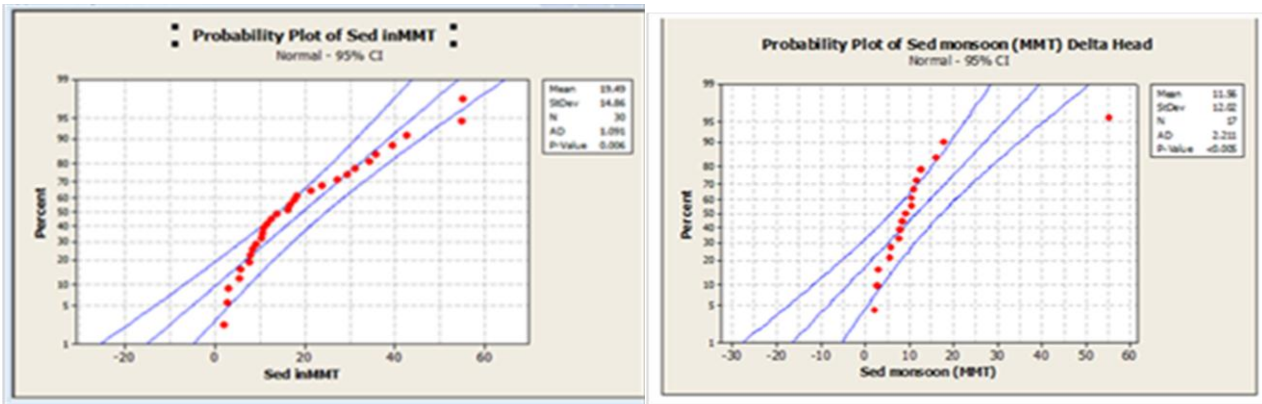

Fig 6 a:- Prob. plot of annual sediment 6 (b) Plot for annual sediment during monsoon (Mahanadi)

Goodness of fit tests:-

The GOF Tests is conducted for Kolmogorov Simronov, Anderson and Darling (A^2) and Chi square the time series data. The ranks of PDF functions for monsoon flow of river Mahanadi by the Log Pearson Type III (LPT-III) methods considered. Their ranks and the parameters of the distributions are given in Tab 6

Table 6:- Best GOF PDF with Ranks and Parameters for Monsoon Flow (Mahanadi) U/S of Naraj

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared		
		Stat	Rank	Stat	Rank	Stat	Rank	Parameters
1	Gumbel Min	0.172	1	1.168	2	0.478	2	□=67.382 □=281.81
2	Log-Pearson 3	0.183	2	0.386	1	0.022	1	□=23.534 □=-0.07624 □=7.2256
6	Log-Logistic (3P)	0.154	8	0.312	6	0.002	2	□=4.2906 □=218.51

Regression Equations:-

Linear and nonlinear regression equations are developed for sediment of river Mahanadi at the upstream of Naraj during SW monsoon. (Tab 7) .

Table 7:- The Nonlinear Regression Equations for Annual Cumulative Discharge vrs Sediment of River Mahanadi (Monsoon 1993-2012)

#	Equation type	Equation	PARAMETERS					R^2 Value
			Y_0	a	b	c	X_0	
1	Power	$Y = a x^b$		$1.6 * 10^{-4}$	1.68			.955
2	Exponential	$Y=a(1-e^{-bx})$		$8.14*10^7$	$3.91*10^{-09}$			.767
3	ln (3para.)	$Y= y_0 + a \ln (x-x_0)$	$-1.59*10^7$	1.08*106			$-2.28*10^6$	.879
4	ln (2nd order)	$Y= y_0 + a \ln (x\ ) + (b \ln x)^2$	$1.98*10^6$	$-3.91*10^5$	$1.93*10^4$			.922
5	ln (3rd order)	$Y= y_0 + a \ln (x\ ) + (b \ln x)^2 + c (\ln x)^3$	$-1.65*10^7$	$4.83*10^6$	$-4.69*10^5$	$1.52*10^4$		.969

From various trial nonlinear regression equations, the time series has the highest R^2 value (0-969) when the PDF model is logarthimic 3rd order equation. But a simple power nonlinear regression equation with almost equals R^2 value can be considered as the relation between the sediment and discharge. The equation is given by:

$$Y_{SS} = 0.0016 * X^{1.68} \quad \text{---- eqn 1.}$$

Where Y_{ss} is the suspended solids in MMT and X is the annual discharge in BCum

Monsoon sediment flow vs. Discharge:-

The time series data plot of discharge vs. sediment and the distribution given in Fig 7 indicate that the two data sets agree to each other.

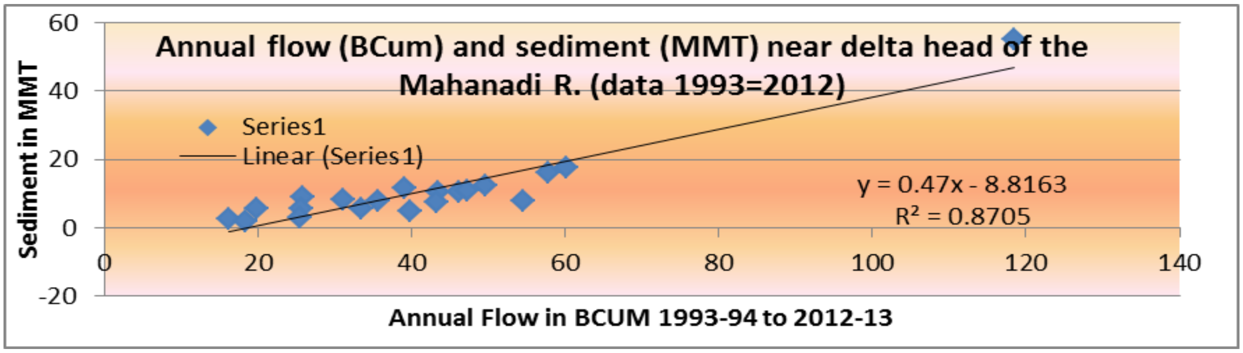

Fig 7:- Relation between flow and sediment near delta head (Source: CWC Data Book).

Estimate of future sediment in the Mahanadi:-

From the rank number and the probability density function curves it is found the lowest curve Log Pearson Type Iii (LPT III) is the best fit curve. LPT III probability density function was used for estimation for future flow of sediment during monsoon period in the Mahanadi River against various recurrence intervals. The estimated flow and sediment in the river at the apex of the delta is given in table 7 and fig 7.

Table 8:- Prediction of Monsoon, Non-monsoon and Annual Discharge, Sediment of River Mahanadi at Delta Head with Various Return Periods

#	Return Period years (p)	Annual monsoon discharge Mcum	Annual monsoon sediment TMT	Annual Dis Mcum	Annual sed TMT
		Gumbel method		Log pearson Type III	
1	1.05	16915	2472	21138	2677
2	1.11	19810	3185	24469	3452
3	1.25	24135	4369	29363	4728
4	2	35936	8246	42341	8823
5	5	54922	16185	62408	16928
6	10	69330	23420	77165	24083
7	25	89621	35166	97443	35386
8	50	106233	46011	113684	45565
9	100	124218	58904	130978	57412
10	200	143713	74137	149428	71141
11	500	172022	98428	175756	92535
12	1000	195651	120556	197393	11160
13	2000	221255	146304	220513	13341
14	5000	253073	180727	248840	16193
15	10000	289489	223265	280813	19654

The estimated discharge and sediment flow in the delta of the river Mahanadi is given in fig 8. From the estimated discharge and sediment at various recurrence interval are slow and have an increasing trend.

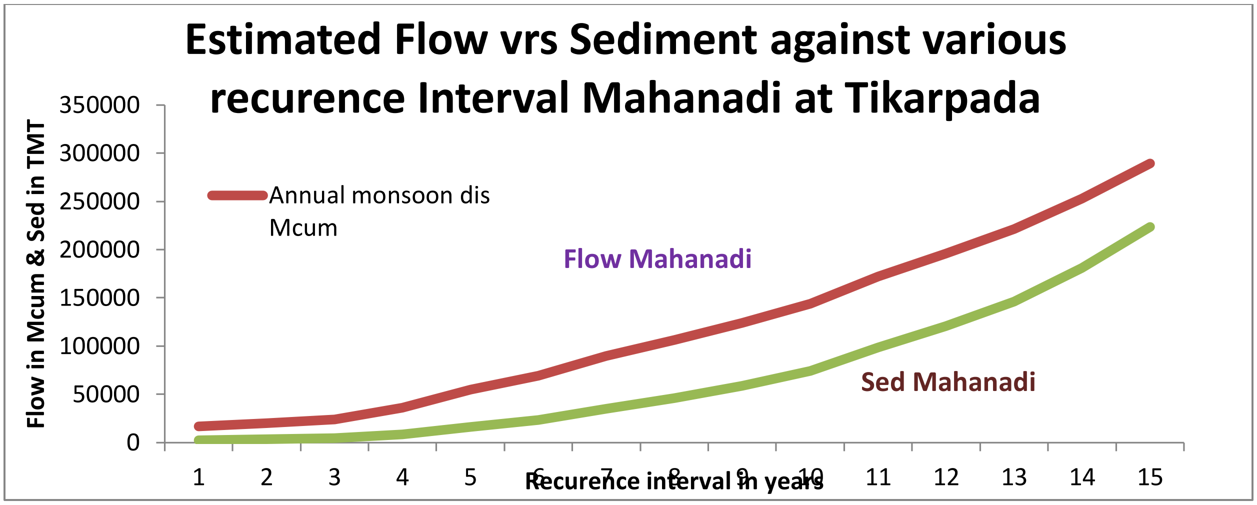

Fig 8:- The predicted flow vs. sediment flow at upstream of delta at various recurrence interval.

Sediment management from SMD to Chilika:-

Sadaf N et al., 2017[50] studied the sediment of the Chilika lagoon and reported that a dynamic ecosystem, Chilika, has plenty of Organic Matter from autochthonous sources and from anthropogenic sources. Hence some operational modification can reduce the stress of sedimentation of the Lagoon Chilika.

Low gradient rivers meanders in deltas (sinuosity > 1.5) are generally unstable. They have high velocities at deeper region at the concave bends and cause bank erosion occurs downstream. At bends centrifugal force plays pivotal role and convert linear fluvial motion to a helical motion which erode the outer bank by building and deposition in reverse bank. The asymmetry in sediment flow across the river section is that finer particles moves inward and coarser along the main. In case of Gabakund cut, major portion of sediment flows along the mainstream and the finer particles along the Gabakund cut during flood. The sediment deposition downstream has been observed from 2007 onwards. The bed of the Bhargovi is silting up. The Gabakund cut is diverting 50 to 60% of flood flow of Bhargovi (Fig 9). The low discharge with high sediment concentration is adding to the problem of sedimentation of the lagoon. In order to provide thresh hold flushing flow to Chillika, the low submerged Gabakund weir of 1.2 m height should be gated. Intermittent release of flash floods by gate regulation in the cut shall create flash floods annually so that the river and the lagoon shall maintain their health (Mishra et al., 2016) [51].

Three barrages are constructed at apex of the delta over three major distributaries the Kathajodi, the Mahanadi and the Birupa. The Naraj barrage over the Kathajodi was constructed for providing flushing flow to regulate sedimentation of Chilika lagoon. The effective operation during drought scenarios is accumulation and release of floods to create a low flash flushing flood for the lagoon. During low/medium floods the barrage should accumulate and intermittently released fragmented floods to make it a numbers of flash flushing flood for the Chilika. In high floods, the Naraj barrage along with other barrages should be operated to retain 15500 cumec in Kathajodi system and releasing rest in other two systems. But during very high floods all the barrages should have all the gates open. (Euro Consultant report: World Bank 2004, and Mishra et al., 2015[41]). However the first flood of the river Mahanadi should not be discharged to the system as the sediment concentration in the first flood is high due to recent tilling
of the agricultural fields before monsoon. The enriched nutrients present in the first flood shall also accelerate growth of aquatic plants, sea grass, different phytoplankton's, Cyan bacteria's and increase further sedimentation in long run.

The nearest Barrage to the Lagoon is the Gobardhanpur barrage on river Bhargovi. The barrage is used for preventing salinity intrusion to the upstream of the river and building irrigation water for summer crops. The regulating structure is nearest to the northern swamp which is suffering from sedimentation. If arrangement can be made to accumulate of river water daily during tides and release of water with ebb tides during non Rabi crops period and no flood period then some flushing flow can be added to save the northern swamps from sedimentation.

Increase of bed level at the confluence points of the ultimately combined the Daya, the Bhargovi, the Nuna and the Ratnachira have been silted up as velocity of flow suddenly drops due to widening just after joining the Chilika. This increases sedimentation and proliferation of weeds (Ipomeas and water hyacinth) in the lower marginal sector of the delta and northern swamps of the Chilika. During flood these fresh water weeds obstruct flow and retains flood in the lower delta for weeks. Removal of those weeds should be prioritized to have a smooth flushing of flood to the Chilika.

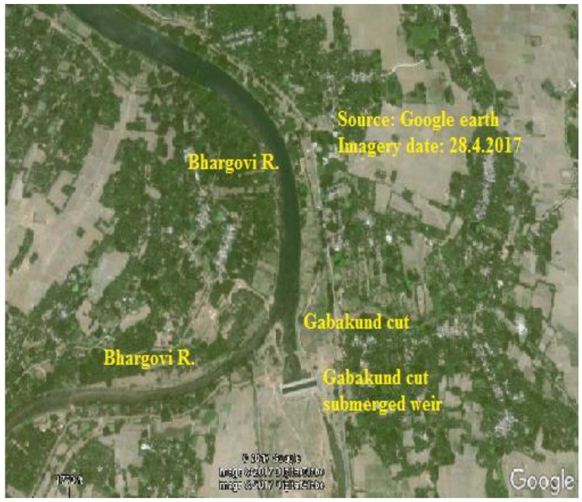

Fig 10:- The map of Bhargovi R & Gabakund cut.

Forestation and effective catchment treatment plans in the watersheds of the Daya and Bhargovi should be taken up to reduce sedimentation, eutrophication in the northern swamps and the rivers. A pre-regulated sand mining should be encouraged in the upper deltaic reaches to deepen and maintain the depth of the river beds

Conclusion:-

The sediment inflow through the south Mahanadi deltaic rivers shows that the Chilika Lake is downsizing both in area and depth due to anthropogenic activities and sediment entry from Mahanadi system. The causes are disparity between sediment inflow during monsoon and tidal ingress during non-monsoon period. Dams above Hirakud are retaining sediment within the reservoirs decreasing flow of sediment to delta from 1985 onwards. Gabakund cut have reduced discharge in fag end of the river Bhargovi. The flushing flows in the Chilika are not achieved regularly. The monsoon sediment concentration in the rivers Daya has been reduced in post Naraj barrage operation.

The effect of Naraj barrage and the Gobakund cut have improved the adequate flushing flow to Chilika but persisted increased sedimentation in the northern sector. Barrages and cuts in the Bhargovi River have less impact on sediment concentration. The proper scientific management only can ameliorate the sedimentation.

On the statistical analysis it is observed LPT III probability density function can be used for estimation for future flow of sediment during monsoon period in the south Mahanadi Rivers transported to the Chilika against various recurrence intervals.

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