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Sedimentation in Major Hydro-power Reservoirs in India- A Review

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Abstract
Almost all rivers of India carry sediments continuously from origin to end. The sediments deposited in the reservoir reduce its capacity and in turn affects the hydro-power generation, hence the estimation of the loss of reservoir capacity in India is of prime importance. However, very few studies are available in this domain that precisely calculates the trap efficiency of reservoir. Also, the available studies in this area have looked at certain parameters to find the sedimentation. The object of this review article is to compare the sedimentation rate of some major reservoirs of India. The climate of India comprises of a wide range of weather conditions across its vast geographic scale and varied topography. It is very difficult to have some generalization regarding the sediment load in river basins, since the sediment particles are generated after undergoing an erosion process in the catchment area. The sediment particles which travel along the river flow settle down on reaching the reservoir and thus lead to loss in capacity of the reservoir.
***Keywords:* *Sedimentation; Trap Efficiency; Capacity-Inflow Ratio; Capacity-Watershed Area Ratio; Sedimentation Index*.**

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I. Introduction

All the rivers of India originate from its three major watersheds, the Himalaya Ranges, the Vindhya & Satpura Ranges and the Sahyadris or the Western Ghat. Rivers of India carry only 5% of the total runoff of the world but they flow with a humongous sediment load of 30% of the total world sedimentation (Milliman and Meade 1983). The entire Himalaya region is seriously affected with the problem of soil-erosion and therefore, the rivers of this region transport a heavy load of sedimentation. The factors responsible for soil erosion are deforestation, mining as well as cultivation on steep slopes. Indian rivers transport nearly $1.2x10^{12}$ kilograms/year or $2.873x10^{12}$ kilograms/year of suspended load into the ocean out of $8x10^{12}$ kilograms/year to $16x10^{12}$kilograms/year of global estimate (DileepKumar et al. 1992 Subramanian 1980; Milliman and Meade 1983). The Vindhya and Satpura ranges are less susceptible to sedimentation problems as compared to the Himalayan Rivers; still the sedimentation rate is unavoidable. Various dams situated in the Vindhya and Satpura region are underperforming in power generation due to loss of storage capacity. The Gandhisagar dam with the second largest reservoir after the Hirakud dam generates only 111 MW, which is 72.86% of actual design power generation, similarly Rana Pratap Sagar generating 47.7% and Jawahar Sagar 32.89% (Thakkar and Bhattacharya 2010). These reservoirs of MP region are the worst performers amongst 4700 large dams built across India in the last 63 years. Future prediction of sedimentation in Indian dams is shown in Figure 1.
Table 1 shows the Annual Average sedimentation value in MCM in the major rivers of northern India.

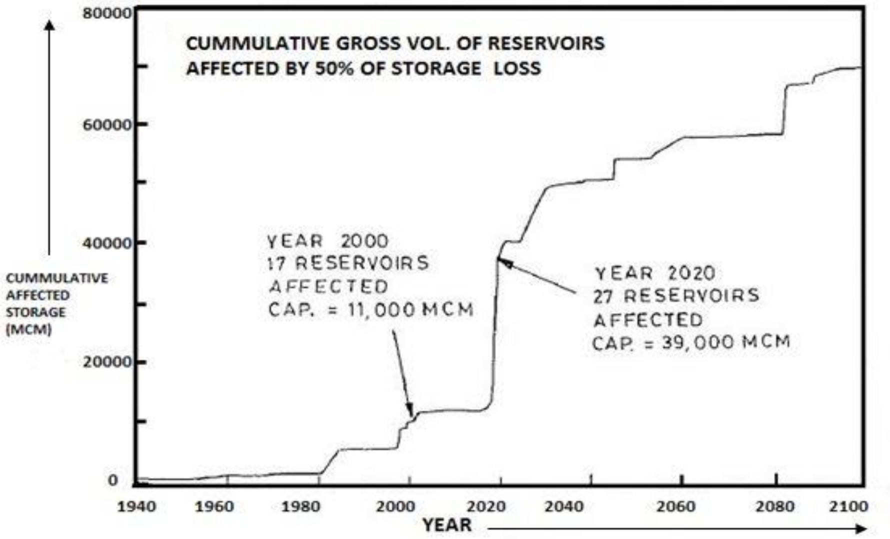

Figure 1: Future Sedimentation in India [Morris 1995]

TABLE 1: SEDIMENTS LOAD ON THE NORTH & NORTHEAST RIVER BASINS

SN	RIVER BASIN	ANNUAL AVERAGE SEDIMENTATION (MCM)
1	Bramhaputra at Pasighat Dam	110
2	Ravi at Chamera-I Dam	6.8
3	Satluj at Bhakra Dam	32.48
4	Vyas at Pong Dam	35.05
5	Chenab at Salal Dam	28.42

Main Rivers in the Western Ghat region are the Krishna, the Kaveri and the Tungabhadra. The silt observation on the Krishna River is being performed systematically and it is observed that Krishna River carries less silt as compared to many other rivers in India. The Srisailum reservoir situated upstream of the Nagarjuna Sagar reservoir, has a dead storage capacity of 4747 Mm^3 whereas Srisailum has the dead load storage capacity of 4461 Mm^3. Furthermore, due to the construction of large number of reservoirs in the upper reach of Krishna and its tributaries, the silt is likely to be trapped in those reservoirs and relatively silt-free water will flow in the Nagarjuna Sagar reservoir. Thus it is very clear that the loss of reservoir capacity due to sedimentation is a big problem in hydropower schemes. It leads to the loss of power generation and the revenue generation of the country since sedimentation is a phenomenon which cannot be stopped completely. Hence the sediment load during the life of a project has to be accounted for in the form of dead storage, while designing the reservoir capacity. There are various methods of estimating the sediment load for any reservoir. Some of the important methods are discussed below.

II. Sedimentation Estimation

- Forecasting the sedimentation using empirical methods.
- Estimation of actual sedimentation in reservoirs.

2.1 **Forecasting the sedimentation using empirical methods**

The empirical methods are generally adopted for the future forecasting during the designing phase of the reservoirs when one has to estimate the approximate total amount of sedimentation on the basis of discharge in the river stream and the capacity of the reservoir. The empirical methods are based on parameters like inflow, capacity of reservoir, sediment inflow, sediment outflow, etc. The ratio of sediment retained in the reservoir to the sediment inflow is known as trap efficiency.

$$\eta_{trap} = \frac{(Sed)in-(Sed)out}{(Sed)in} \quad \text{eq.(1)}$$

Various methods used for calculating the trap efficiency are explained as follows:

Capacity Watershed or Brown's Curve Method

Brown developed an empirical relationship in the form of curves between trap efficiency (η in %), reservoir capacity (C in acre-feet), watershed area (W in square-miles). The equation for this curve (Figure 2) is as follows:

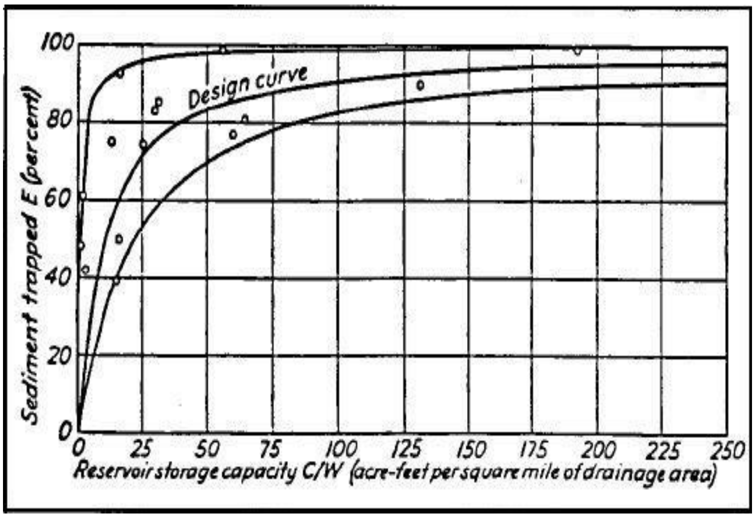

Figure 2: Brown's Curve [EM 1110-2-4000 1989]

$$\eta_{trap} = 100\ X \left(1 - \frac{1}{1+\frac{C}{W}}\right) \qquad \text{eq.(2)}$$

Where K is a coefficient which ranges from 0.046 to 1 with a mean value of 0.1 also depends upon time of the region, average grain size and reservoir operation that prohibit the movement of sediment toward outlet (USACE 1995). The variation of k is generally due to the fact that reservoirs having the same C/W ratio can have the same C/I ratio. Brown's method is useful only when the watershed area and the reservoir capacity are known.

2.1.2 Capacity Inflow Method or Brune's Method

In this method, Brune represented a relationship between trap efficiency and the C/I ratio in the form of envelope curves. These envelope curves were generated using the data of normally ponded reservoirs. These curves are not useful in determining the trap efficiency for dry reservoirs. Dendy developed an equation for the mean Brune's curve (Figure 3) as:

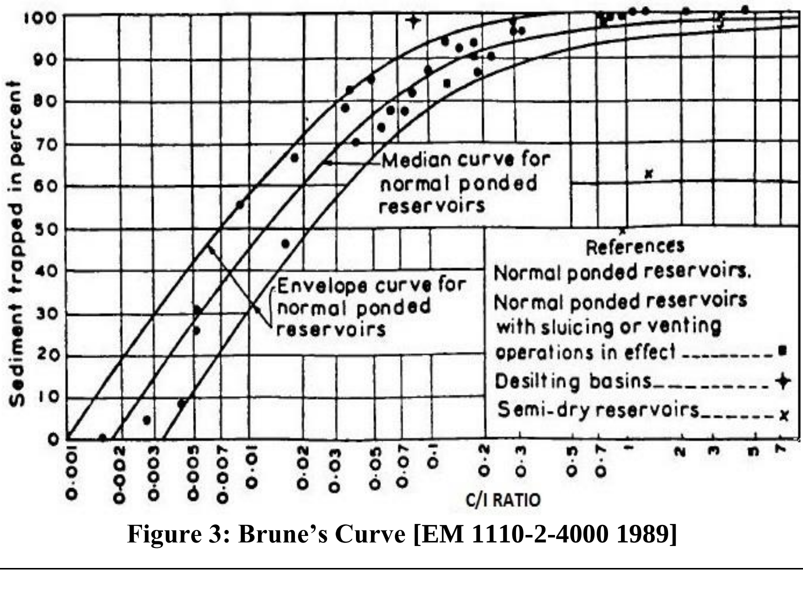

Figure 3: Brune's Curve [EM 1110-2-4000 1989]

$$\eta_{trap} = 100\left(0.97^{0.19^{log\frac{C}{I}}}\right) \qquad \text{eq.(3)}$$

2.1.3 Churchill's Curve

In 1948, Churchill established a co-relation between sedimentation index and trap efficiency. The term, Sedimentation Index can be defined as the ratio of retention period (R) to the reservoir mean velocity (V). If field data of retention time and velocity is not available, C/I ratio can be used instead. By this method, we can find the sedimentation index and by deducing the value of sedimentation index from 100, we can find the value of trap efficiency. The variation of sedimentation index and trapped sediments is given in Figure 4. The comparison between all three methods is given in Table 2.

TABLE 2: COMPARISON TABLE

SN	FIELD	BROWN'S METHOD	BRUNE'S METHOD	CHURCHILL'S METHOD
1	SIMPLICITY	MOST SIMPLE	LESS SIMPLE	HARD
2	ACCURACY	LESS ACCURATE	MORE ACCCURATE	LESS ACCURATE
3	DATA REQUIRED	CAPACITY, WATERSHED AREA	CAPACITY, INFLOW	CAPACITY, INFLOW RESERVIOR LENGTH

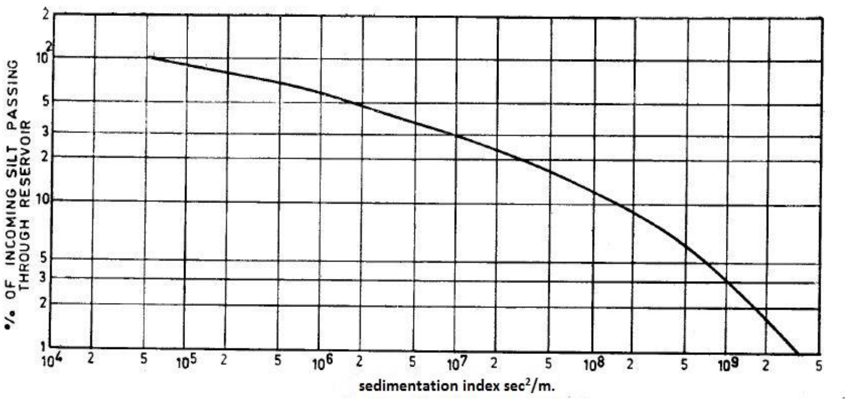

Figure 4: Churchill's Curve [EM 1110-2-4000 1989]

$$\textbf{Sedimentation Index} = \left(\frac{R}{V}\right) \qquad \textbf{eq. (4)}$$

$$\textbf{R} = \left(\frac{C}{I}\right) \qquad \textbf{eq. (5)}$$

$$\textbf{V} = \left(\frac{I}{A}\right) \qquad \textbf{eq. (6)}$$

$$\textbf{A} = \left(\frac{C}{L}\right) \qquad \textbf{eq. (7)}$$

$$\textbf{Sedimentation Index} = \left(\frac{\left(\frac{C}{I}\right)^2}{L}\right) \qquad \textbf{eq. (8)}$$

Estimation of actual sedimentation in reservoirs

These methods are used to predict the actual sedimentation in the reservoirs after the construction using satellite images. The remote sensing method calculates the decrement in the water spread area at various elevations which is mainly due to the sedimentation. These water spread areas are calculated from the satellite image finding the reservoir level, thereby establishing the elevation versus capacity curve.

Remote Sensing Method

The method of remote sensing for finding the sedimentation has been used by various researchers (Bartolucci et al. 1977; Holeyer1978; Khorram 1981; Solomonson 1973). In a study, researchers have (Smith et al. 1980) calculated the sedimentation in the Aswan Dam by comparing the values of red and green spectrum; the surface area of entire reservoir was determined by adding all pixel categories as water. Research showed that silting during the flood period was largely limited to the main river of the dam. Thus, the area of sedimentation was found and the amount of deposition was determined. (Rao et al. 1985) used a different technique of large scale image of Landset-MSS to find the area of water bodies at various level of Sri Ram Sagar dam and found that the data is comparable to the hydrographic survey. The image data used in this study was provided by Indian remote sensing satellite Liss-III sensor having spectral resolution in 4 bands (0.52-0.59, 0.62-0.68, 0.77-0.86, 1.55-1.7 µm).The sub-pixel and linear mixture model approach was used to find the water-spread area of the reservoir. Thereafter using the trapezoidal rule the storage capacity of the reservoir is estimated.

III. Sedimentation in some hydropower schemes

Central water commission (CWC) has published a report in 2015 based on the sedimentation studies conducted on various major dam schemes of India. The average rate of sedimentation for these dams is shown in Figure 5. The results of the sedimentation studies of various dams are discussed below.

3.1 **Sedimentation in Bhakra Reservoir**

The sediment problem is very common in Himalayan region (Sharma et al. 1991). Due to shifting cultivation a total of 30,000 Km^2 have been seriously eroded in the North-East Himalaya (Narayan and Babu 1983). Due to the presence of high altitude, the glacier in the Himalaya region also imparts a high rate of sedimentation (Singh 2001). According to the result of sedimentation survey on the reservoir in 1997, it was found that during a period of 32 years (1967-1997), the loss in the storage capacity of the reservoir was about 668.28 Mm^3, loss in live storage was about 666.85Mm^3 while the average rate of sedimentation was found to be 20.88 Mm^3 per year (Jain et al. 2002).

CWC has been conducting frequent sedimentation studies for this reservoir and results of these surveys have been summarized in the form of a table (Table 3). In a report published in 2015 by CWC they have conducted the sedimentation study 32 times starting from 1959 to 2012 at different time intervals. The highest rate of sedimentation was observed in 1988-1990 which was 59.735 MCM/yr. The average rate of sedimentation of this reservoir for 54 years (1958-2012) is 38.858 MCM/yr.

TABLE 3
SEDIMENTATION IN BHAKHRA RESERVOIR

SN	SURVEY YEAR	PERIOD (YEAR)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	1958	-	-	-
2	1959	1	0.16	0.16
3	1963	4	143.31	35.827
4	1965	2	92.61	46.305
5	1966	1	24.21	24.21
6	1967	1	51.7	51.7
7	1968	1	32.46	32.46
8	1969	1	16.44	16.44
9	1970	1	44.7	44.7
10	1971	1	14.84	14.84
11	1972	1	30.04	30.04
12	1973	1	22.14	22.14
13	1974	1	53.56	53.56
14	1975	1	20.85	20.85
15	1976	1	35.73	35.73
16	1977	1	25.43	25.43
17	1979	2	99.5	49.75
18	1981	2	69.18	34.59
19	1983	2	56.52	28.26
20	1984	1	27.34	27.34
21	1986	2	74.34	37.17
22	1988	2	77.22	38.61
23	1990	2	119.47	59.735

24	1992	2	54.68	27.32
25	1994	2	96.28	48.14
26	1996	2	51.8	25.9
27	1998	2	55.85	27.925
28	2000	2	92.06	46.03
29	2002	2	63.82	31.91
30	2005	3	177.89	59.197
31	2007	2	101.72	50.86
32	2009	2	112.39	56.195
33	2012	3	160.4	53.46

3.2 **Sedimentation in Gandhi Sagar Reservoir**

In Madhya Pradesh region, Chambal River is quite prone to soil erosion. It is mostly affected by gully erosion. According to (Morris 1995) the rate of sedimentation was found to be 0.96 TMC per year. The dam was constructed in 1960 and from 1960-2001, a total of three studies have been performed by CWC. The highest rate of sedimentation was 22.2 MCM/yr in the duration of 1960-1975 and the average rate of sedimentation observed was 12.68 MCM/yr in last 41 years. Details of the sedimentation studies are given in the Table 4.

TABLE 4
SEDIMENTATION IN GANDHI SAGAR RESERVOIR CWC REPORT 2015

SN	SURVEY YEAR	PERIOD (YEARS)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	1960	-	-	-
2	1975	15	333	22.2
3	1989	14	90	6.429
4	2001	12	96.85	8.071

3.3 **Sedimentation in Hirakud Reservoir**

Hirakud dam impounds one of the largest reservoirs in India built across Mahanadi River. The 55 kilometers long dam was constructed to create the first multipurpose reservoir in India after independence. According to a sedimentation study done in 1999-2001 by National Institute of Hydrology, Roorkee, the actual utilizable volume of the reservoir was 5818Mm^3 and gross volume was 8136 Mm^{3}respectively. The MDDL and FRL were 179.83 and 192.02 meters respectively and the modified live storage capacity was 4842 Mm^3.

According to one more study which was conducted in 1989 (Mukherjee et al. 2007) it was concluded that from 1957 to 1989 the loss in capacity was 1953.7 MCM (24%) and the annual rate of siltation for this period was found to be 61.05 MCM since the starting of reservoir from 1957, elevation capacity curve of the study is given in Figure 6. The reservoir capacity between two consecutive elevations was determined using Cone's formula (Murthy 1969).

$$\mathbf{V} = \frac{\mathbf{h}}{\mathbf{3}}\left(A_1 + A_2 + \sqrt{A_1 A_2}\right) \qquad \text{eq. (9)}$$

Where,

V = Volume between two successive elevations

h = Difference in elevation

A_1& A_2 = Area of reservoir corresponding to h_1& h_2

According to the CWC 2015 report, total five sedimentation studies have been performed by CWC in this reservoir. The highest rate of sedimentation 153.924 MCM/yr. was observed during 1979-1981. The average rate of sedimentation for the last 43 years (1957-2000) was 51.4 MCM/yr. ; details are discussed in Table 5.

TABLE 5
SEDIMENTATION IN HIRAKUD RESERVOIR CWC REPORT 2015

SN	SURVEY YEAR	PERIOD (YEARS)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	1957	-	-	-
2	1979	22	1170.74	53.216
3	1981	2	307.85	153.924
4	1986	5	12.65	2.529
5	1991	5	403.76	80.753
6	2000	9	315.21	35.023

3.4 **Sedimentation in Srisailam Reservoir**

Srisailam dam is situated in Kurnool, Andhra Pradesh across the Krishna River. The Srisailam dam is situated in the narrow gorge of Krishna Valley. The project is located 869 kilometers downstream from the origin of the river. The Srisailam reservoir has a water spread area of 616Km^{2}and an estimated live capacity of 178.74 TMC-feet. The full reservoir level is 270 meters. The reservoir has a catchment area of 206030 Km^2. According to a remote sensing study conducted in 2004, the annual rate of loss in live storage was 0.846%. The total sedimentation deposit in 28 years (1976-2004) was 1960.84 MCM (Narasayya 2013). On the basis of CWC report 2015 based on the three studies conducted during 2001 to 2011, the highest rate of sedimentation was reported to be 104.4 MCM/yr during 2006-2010 while the average rate of sedimentation for the last 35 years (1976-2011) was 74.68 MCM/yr. The details of these studies are given in Table 6.

TABLE 6
SEDIMENTATION IN SRISAILAM RESERVOIR CWC REPORT 2015

SN	SURVEY YEAR	PERIOD (YEARS)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	1976	-	-	-
2	2001	25	2479.6	99.19
3	2006	5	-387.65	-
4	2011	5	522.02	104.4

3.5 **Sedimentation in Nagarjuna Sagar**

The length of Krishna valley is around 45 kilometers and the area covered by the same is about 320 Km^2. The range of tide covers 39 K.m. upstream in the Penikudi region. The main width of estuary is about 1.2km with an average depth of 5-7 meters. Nagarjuna Sagar built across Krishna River is one of the largest masonry dam and also one of the earliest multipurpose reservoirs in India. The dam is suffering from sedimentation problem and sedimentation studies have been conducted twice in 2001 and 2009 by CWC. As per these studies the average rate of sedimentation was 65.984 MCM/yr for 1967-2001 and 59.19 MCM/yr for 2001-2009 respectively. The average rate of sedimentation for the total duration (1967-2009) is 64.689 MCM/yr as per the details of the studies given in Table 7.

TABLE 7
SEDIMENTATION IN NAGARJUNA SAGAR RESERVOIR CWC REPORT 2015

SN	SURVEY YEAR	PERIOD (YEARS)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	1967	-	-	-
2	2001	34	2243.44	65.984
3	2009	8	473.51	59.19

3.6 **Sedimentation in Tehri Reservoir**

The Tehri dam is the highest dam in India and the 10thtallest dam in the world. It is a multipurpose dam which is an Earth-fill embankment type of dam built across Bhagirathi River in Tehri district of Uttrakhand. The height of the dam is 260.5m and its length is 575m. Catchment Area Treatment (CAT) had been done for the project in order to reduce soil erosion as the entire area lies in the region of very high soil erodibility. According to (Panda and Bandopadhyay 2010) the Bhagirathi River draws a large amount of sediments from the river Ganga at Jangipur. According to CWC report published in 2015 they have conducted the sedimentation study only once in 2008 after the construction of the dam. The loss in capacity of Tehri Dam is 7.003 MCM/yr for the period of (2005-2008) given in Table 8.

TABLE 8
SEDIMENTATION IN TEHRI RESERVOIR CWC REPORT 2015

SN	SURVEY YEAR	PERIOD (YEARS)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	2005	-	-	-
2	2008	3	21.01	7.003

3.7 **Sedimentation in Koyna Reservoir**

Konya dam is the second largest hydropower reservoir of India. The total capacity of the dam is 1960 MW. The project compromises of 4 stages of power generation. It is a rubble concrete dam on Koyna River. A bathymetric survey was done in 2004 (Patil and Shetkar 2015) and on the basis of this survey it has been concluded that the loss in capacity for 39 years (1969-2004) was 293.09 MCM and the average rate of sedimentation was 7.515MCM/yr. According to the CWC report (2015) the sedimentation study for this reservoir was conducted only once in 2012. Based on this study the average rate of sedimentation for 50 years (1962-2012) was determined as 3.476 MCM/yr. (Table 9).

TABLE 9
SEDIMENTATION IN KOYNA RESERVOIR CWC REPORT 2015

SN	SURVEY YEAR	PERIOD (YEARS)	CAPACITY LOSS SINCE LAST SURVEY (MCM/YR)	RATE OF SEDIMENTATION (MCM/YR)
1	1962	-	-	-
2	2012	50	173.791	3.476

IV. Conclusion

This study shows that sedimentation in large hydropower reservoirs is taking place at an alarming rate. On the basis of this study we can draw the following conclusions.

- The total capacity of the dams of India is decreasing drastically due to sedimentation. In fact, some of the major reservoirs are going to lose 50%of their capacity by 2020.
- There is a large variation in the sediment rate over different basins. The Ram Ganga reservoir of U.P has almost the same total capacity as Sri Ram Sagar of A.P but the siltation rate in Sri Ram Sagar is higher than that of Ram Ganga dam. In fact, Sri Ram Sagar has lost 25% of the total capacity in the first 14 years.
- The sedimentation not only affects the reservoir capacity but also reduces the power generation of the dam and thus affects the cultivation of crops.
- Various catchment area treatment methods need to be implemented on a priority basis for nearly all the major dams of India for increasing the life of their reservoirs.

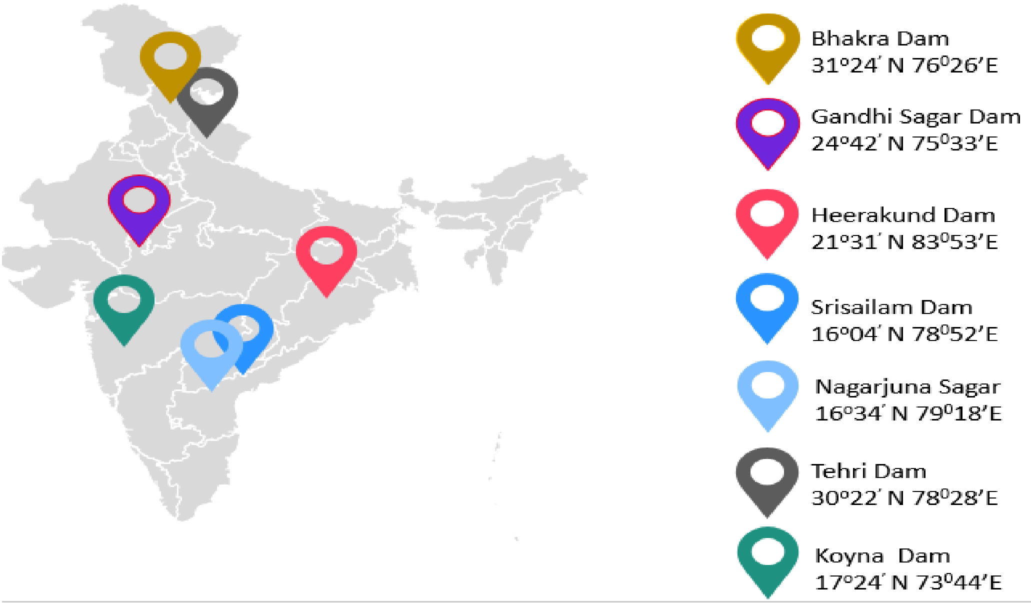

Figure 5: Location of the above Reservoirs

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