SEDIMENTATION STUDY IN A RESERVOIR USING REMOTE SENSING TECHNIQUE

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Abstract. Reservoir sedimentation is a severe problem faced by dams caused due to soil erosion which is almost immeasurable at source and occurs in the catchment areas of the reservoirs. The present study describes the evaluation of sedimentation carried out for Vaigai reservoir situated in Tamil Nadu, India. Vaigai reservoir nourishes the inhabitants through water storage and supply for irrigation and water power. Nowadays, capacity loss occurs in the reservoir due to sedimentation. As it is highly tedious and uneconomical to do hydrographic surveys, the frequentness in finding the sediment yield becomes impossible. But the recent application of remote sensing and GIS technologies in the field of Civil Engineering make it possible. The Satellite Remote Sensing (SRS) method for prediction of reservoir sedimentation uses directly the water-spread area of the reservoir at a particular elevation on the date of pass of the satellite. With known area and the difference in level of water, the capacity and thereby the loss in capacity of the reservoir due to sedimentation can also be estimated. This paper illustrates the prediction of sedimentation at Vaigai reservoir using remote sensing and ArcGIS.
Keywords: *sedimentation, remote sensing, reservoir, water spread area, capacity*

Introduction

Reservoirs are built across rivers for the purpose of irrigation, water supply, power generation, discharge regulation and flood control. A reservoir will generally be located towards the end of a large watershed and receives inflows from major rivers (Jørgensen et al., 2005). On the other hand, reservoirs have a shorter residence time but a much larger watershed which can be more difficult to control (Randolph, 2004). Rainfall, runoff, snowmelt, and river channel erosion provide a continuous supply of sediment that is hydraulically transported and deposited in rivers and streams. The major advantages of dams are in flood control and in transferring water to areas with deficit of water (Wang et al., 2003; Mukherjee et al., 2007; Goel et al., 2002). There are many reservoirs that can no longer perform their design functions because much of their original active storage volume has been filled by sediment (Ijam and Al-Mahamid, 2012). The transported silt eventually gets deposited at different levels of a reservoir and reduces its storage capacity (Goel et al., 2002; Jain et al., 2002; Sreenivasulu and Udayabaskar, 2010). When the river flow enters a reservoir, due to the very low velocity in reservoirs, they tend to be very efficient sediment traps. Hence transport capacity is reduced and the sediment load is deposited in the reservoir. This deposition which takes place gradually reduces the active capacity of the reservoir and fails to

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provide the outputs of water with passage of time. Despite the fact that soil erosion can be caused by geomorphologic process, accelerated soil erosion is principally favored by human activities. Rapid population growth, deforestation, un- suitable land cultivation, uncontrolled and overgrazing have resulted in accelerated soil erosion in the world principally in developing countries like Ethiopia (Adebe and Sewnet, 2014; Tamene et al., 2006). All reservoirs formed by dams on natural rivers are subject to some degree of sediment inflow and deposition. Worldwide, around 40,000 large reservoirs suffer from sedimentation and it is estimated that between 0.5% and 1% of the total storage capacity is lost per year. Therefore, the amount of sedimentation all through the life of the project needs to be estimated, so that suitable conservation measures can be taken. Periodical capacity surveys of the reservoir help in assessing the rate of sedimentation and reduction in storage capacity (Jeyakanthan and Sanjeevi, 2013). A Geographical Information System (GIS) can be used to model bathymetry and the spatial distribution of sediments (Evans et al., 2002). Several attempts have been made to calculate the quantity of sediment using remote sensing technology (Yeo et al., 2014; Narasayya et al., 2013; Sri Sumantyo et al., 2012).Using the Remote Sensing techniques, it has become very efficient and convenient to quantify the sedimentation in a reservoir and to assess its distribution and deposition pattern (Narasayya et al., 2013). Remote sensing technology, offers data acquisition over a long period of time and broad spectral range, can provide synoptic, repetitive and timely information regarding the sedimentation characteristics in a reservoir. Water spread area of the reservoir for a particular elevation can be obtained very accurately from the satellite data. Reduction if any, in the water spread area for a particular elevation indicates deposition of sediment at that level. When it is integrated over a range of elevations using multi-date satellite data enables computing volume of storage lost due to sedimentation.

Materials and methods

Study area

The Vaigai Dam is built across the Vaigai River in Periyar Vaigai Basin near Andipatti, in the Theni district of Tamil Nadu, Southern India as shown in *Figure 1*.

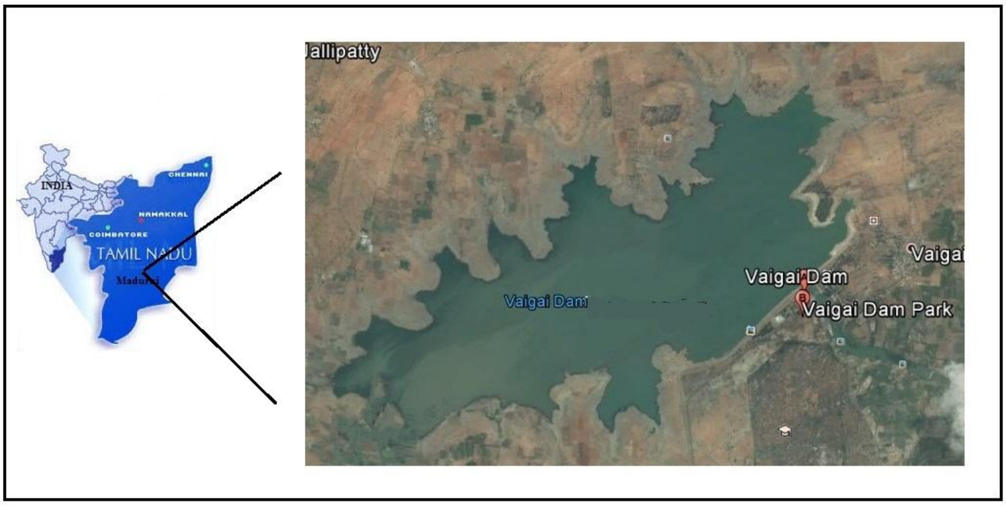

Figure 1. *Location Map of Vaigai Reservoir*

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It is situated between $9^0 30'$ and $10^0 10'$ North Latitudes and $77^0 10'$ and 77^0 $40'$ East Longitude. The Vaigai reservoir project get started on January 10th, 1955 and completed on September, 1958. This is a multipurpose reservoir. It provides water for irrigation to Madurai and Theni district, drinking water to Madurai and Andipatti as well as facilitates hydroelectric power generation to the extent of 6 MW. The catchment area comprises of Cumbum Valley, Varushanadu valley, Varushanadu hills and Western Ghats. The Central area is low lying and consists of fertile irrigated wetland. Vast stretch of denuded forest spreads over the watershed along the plains of Varushanadu hills. The total catchment area of the reservoir is 2255.127sq.km and the FRL of the reservoir is 279.197 m. The Live storage of the reservoir lies between RL 257.556m and RL 279.197 m. The dead storage capacity lies between RL 249.936 m and RL 257.556 m. The Capacity of the reservoir at maximum water level is 194.785 Mm^3. The general climate of the watershed is sub-tropical with temperature varying from 30^0C to 35^0C. During summer months of April to June the hot weather prevails. The catchment receives rainfall from both North East and South West monsoons. The rainfall during South West Monsoon is comparatively less as it is at rain shadow region. The annual maximum rainfall varies from 1017.5 mm to 1586.9 mm. In general, the soils are of deep sandy loam with reddish colour. The area is built with Archean rocks, which compose of gneiss, mica, quartzite, granites and veins of pegmatites and quartz veins.

Data used

Satellite Images of IRS-P6 LISS-III at six overpass dates including 3rd August 2009, 17th March 2009, 10th January 2012, 1st April 2012, 5th March 2005 and 18th June 2005, from which the water spread areas were computed. These images were obtained from National Remote Sensing Agency, Hyderabad, India. Accordingly the Survey of India toposheets of 1:50,000 scales were used (Narasayya et al., 2013). Report of Sedimentation studies done during the fourth capacity survey of Vaigai reservoir in the year 2000 was used. Elevation- Capacity – Sedimentation data for the years 1958, 1976, 1981 and 1983 are shown in *Table 1*. Water spread area map/ Base Map of scale 1:3960 and the water elevations of the reservoir at different dates were obtained from the Office of the Public works Department at Vaigai dam.

Table1. *Sediment and Capacity data of Vaigai reservoir for the years 1958, 1976, 1981 and 1983*

Sl. No	Elevation in m	Depth from deep bed level	% of depth	Capacity in 1958 in Mm^3	Capacity in 1976 in Mm^3	Capacity in 1981 in Mm^3	Capacity in 1983 in Mm^3	Sediment Deposit of 1983 in Mm^3	% of Sediment
1	249.936	0.000	0.000	-	-	-	-	-	-
2	257.556	7.620	26.041	1.456	0.079	-	-	1.456	6.499
3	258.000	8.064	27.559	1.732	0.125	-	-	1.732	7.730
4	260.000	10.064	34.394	3.583	0.536	0.186	0.194	3.389	15.126
5	262.000	12.064	41.223	7.002	1.845	1.026	1.129	5.873	26.213
6	264.000	14.064	48.064	12.115	4.906	3.295	3.466	8.649	38.603
7	266.000	16.064	64.899	20.338	10.489	8.346	8.118	12.220	54.541
8	268.000	18.064	61.734	31.988	19.634	16.885	16.010	15.978	71.314
9	270.000	20.064	68.569	46.436	33.525	29.294	28.720	17.716	78.072
10	272.000	22.064	75.404	67.867	52.102	47.515	47.249	20.618	92.024
11	274.000	24.064	82.239	93.407	77.006	72.128	72.264	21.144	94.372
12	276.000	26.064	89.074	126.093	109.567	104.494	104.739	21.359	95.381
13	278.000	28.064	95.909	166.649	149.688	144.294	144.399	22.250	99.308
14	279.197	29.261	100.00	194.785	178.191	172.439	172.380	22.405	100.000

Source : Sedimentation survey report of vaigai reservoir

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Review of past sedimentation surveys

The reservoir sedimentation problem depends upon the parameters like type of catchment, nature of catchment, geology, slope and terrain, rainfall, climate, vegetal cover, human activities etc. No universal solution is available for tracking the sedimentation problem because every reservoir is having differences in the above said parameters. Hence it is necessary that every reservoir has to be surveyed periodically. After inception of the reservoir in 1958, the first, second, third and fourth surveys were carried out during 1976, 1981, 1983 and 2000 respectively under the Watershed Management Board Scheme. The comparative sedimentation survey report for the years 1958, 1976, 1981 and 1983 are listed in *Table 1*. The report of the fourth sedimentation survey carried out in the year 2000, including the water spread area and capacities of the reservoir at different water levels are listed in *Table 2*.

Table2. *Capacity chart of vaigai reservoir for various elevations during the year 2000*

Sl. No	Elevation in M	Water spread area in Mm^2	Capacity for the corresponding elevation in Mm^3
1	257.556	0	-
2	258.000	0.0160	0.0036
3	260.000	0.1060	0.1256
4	262.000	0.3596	0.5366
5	264.000	1.1560	1.9258
6	266.000	2.8713	5.7732
7	268.000	5.3031	13.8887
8	270.000	7.7265	26.9800
9	272.000	10.1010	44.7621
10	274.000	13.6646	68.1768
11	276.000	17.7530	99.7704
12	278.000	21.6970	139.0925
13	279.197	24.1524	166.5334

Methodology

Computation of water spread area of Vaigai reservoir

The Survey of India (SOI) toposheets for the Vaigai reservoir have been obtained, scanned and geometrically corrected to represent correct geographical coordinates at each point. Satellite Images of IRS-P6 LISS-III have been georeferenced with respect to toposheets and mosaiced using Arc GIS 9.3.1. The drainage network (streams and tributaries) and the catchment have been identified from the mosaiced toposheet and updated from satellite imagery. The catchment was divided into subcatchments to find its water spread area. The work has been carried out using Digital Image Processing software Arc GIS. The digitally processed images of Vaigai Reservoir showing its water spread area for six overpass dates such as 3rd August 2009, 17th March 2009, 10th January 2012, 1st April 2012, 5th March 2005 and 18th June 2005 are shown in *Figure 2*.

Table 3 shows satellite-derived reservoir water spread areas for different satellite overpass dates along with the water levels of the reservoir at the corresponding dates collected from the Office of the Public Works Department at Vagai Dam. *Figure 3*

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shows the curve between elevation and water spread area obtained through remote sensing data. From *Table 2*, the water spread area at the intermediate elevations (reservoir elevations on the dates of satellite pass) of the sedimentation survey conducted in the year 2000, were obtained by linear interpolation. Using those details, the elevation-area curve for the year 2000 is plotted along with the details of satellite derived. Any shift in the curve will indicate the loss in capacity of the reservoir due to sedimentation. Such shift in the updated elevation- area curve of Vaigai reservoir shown in *Figure 4* represents that there will be capacity loss in Vaigai reservoir due to sediment deposition.

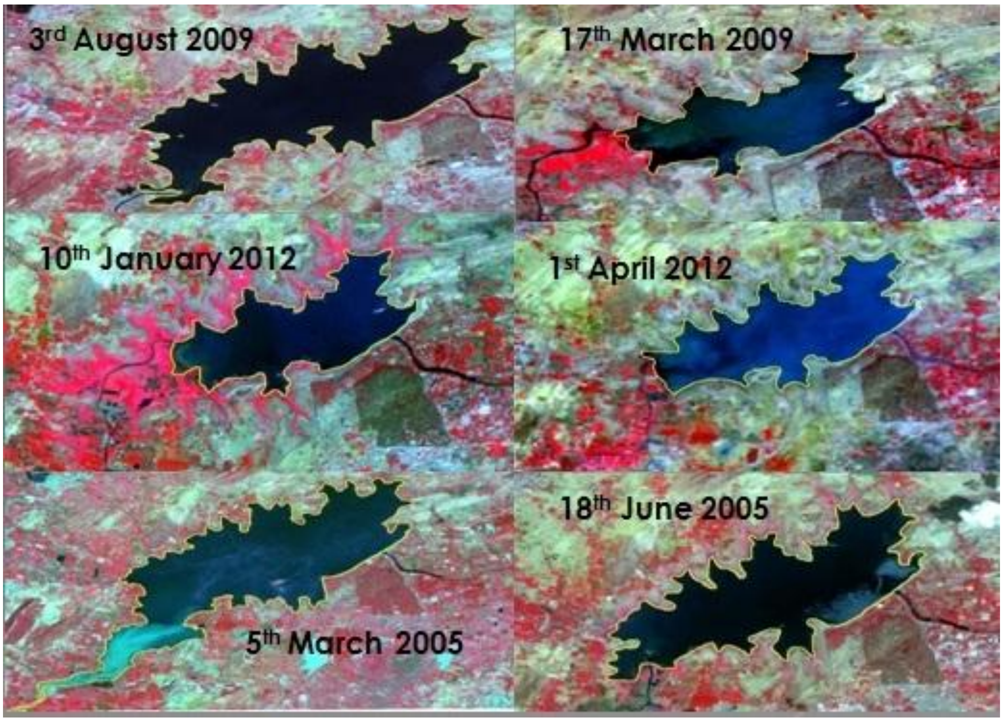

Figure 2. *Digitally processed satellite images representing the water spread area for different overpass dates such as 5thMarch 2005, 18th June 2005, 17th March 2009, 3rd August 2009, 10th January 2012, 1st April 2012*

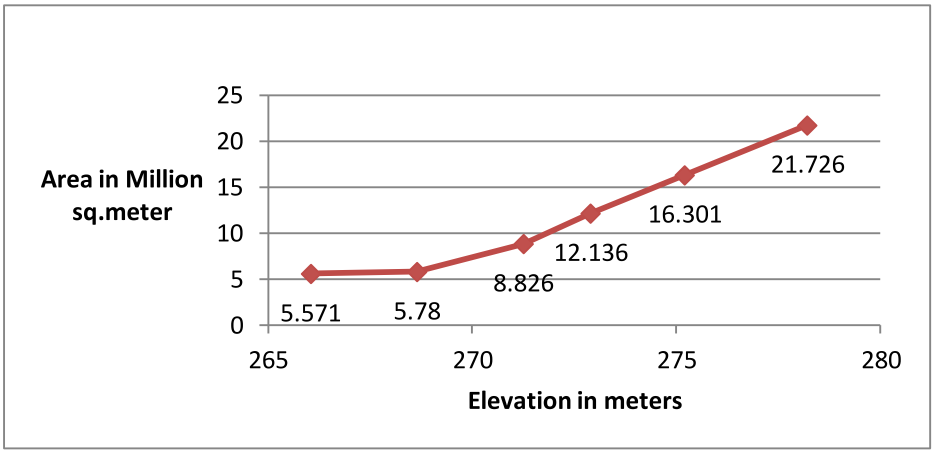

Figure 3. *Satellite derived elevation-area curve (Areas noted are the water spread area for different satellite over pass dates and the corresponding elevations are plotted)*

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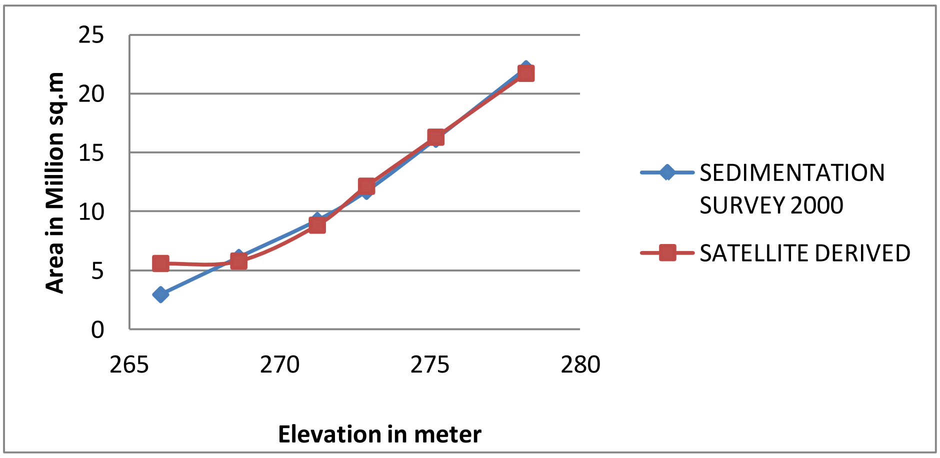

Figure 4. *Comparative elevation-area curve for satellite derived data and sedimentation survey report*

Assessment of Vaigai reservoir capacity

The reservoir capacity between two successive elevations can be assessed using the Cone formula:

$$\mathbf{V = \Delta H\,(A_1 + A_2 + \sqrt{A_1 * A_2})/\,3} \qquad \text{(Eq.1)}$$

Where V – Volume / Capacity between two consecutive elevations 1 and 2
A_1 and A_2 – Water spread areas of reservoir at elevations 1 and 2
ΔH- difference between elevations 1 and 2

On adding the successive volumes between elevations the cumulative capacity above the lowest elevation can be calculated. *Table 3* shows the capacities between elevations and cumulative capacities.

Table 3. *Elevation, Water Spread Area and Capacity chart of Vaigai Reservoir for different satellite overpass dates*

Sl. No	Satellite Overpass Dates	Elevation (m)	Water Spread Area ($Mm^{2)}$)	Capacity between elevations ($Mm^{3)}$)	Cumulative Capacity Mm^3
1	18-6-2005	266.044	5.571		-
2	17-3-2009	268.644	5.780	14.752	14.752
3	3-8-2009	271.256	8.826	18.936	33.688
4	1-4-2012	272.896	12.136	17.116	50.804
5	5-3-2005	275.202	16.301	32.669	83.473
6	10-1-2012	278.206	21.726	56.921	140.394

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Estimation of Vaigai reservoir capacity loss

The loss in capacity can be obtained by comparing the capacity data computed through remote sensing and capacity data obtained during 1st and 4th sedimentation survey of years 1958 and 2000 respectively. The comparison between elevation-capacity of the years 1958, 2000 and satellite derived data are shown in *Table 4*. The volume of sediment is the difference of capacity of years 1958 and 2000 and that obtained through satellite data, which can be treated as the loss of capacity due to sedimentation. The comparative capacity elevation curves for the years 1958, 2000 and satellite derived dates are shown as *Figure 5*. The shift in capacity curves in different years as compared to original capacity curve represents the loss in capacity or sediment deposited at different levels.

Table 4. *Chart representing the Capacity loss due to sedimentation in Vaigai reservoir for the years 2000 and 2012*

Sl. No	**Observed elevation (m)**	**Water Spread area (Mm^2)**	**Cumulative Capacity (Mm^3)**			**Capacity Loss (Mm^3)**	
1	257.556	**RS* 2012**	**1958**	**2000**	**RS* 2012**	**2000**	**RS* 2012**
2	266.044	5.571	20.594	5.951	-	14.643	-
3	268.644	5.780	36.640	18.102	14.752	18.538	21.888
4	271.256	8.826	59.894	38.147	33.688	21.747	26.206
5	272.896	12.136	78.466	55.215	50.804	23.251	27.662
6	275.202	16.301	113.051	87.164	83.473	25.887	29.578
7	278.206	21.726	171.495	143.819	140.394	27.676	31.101
8	279.197	23.183	194.785	166.533	162.620	28.252	32.164

*Remote Sensing Data

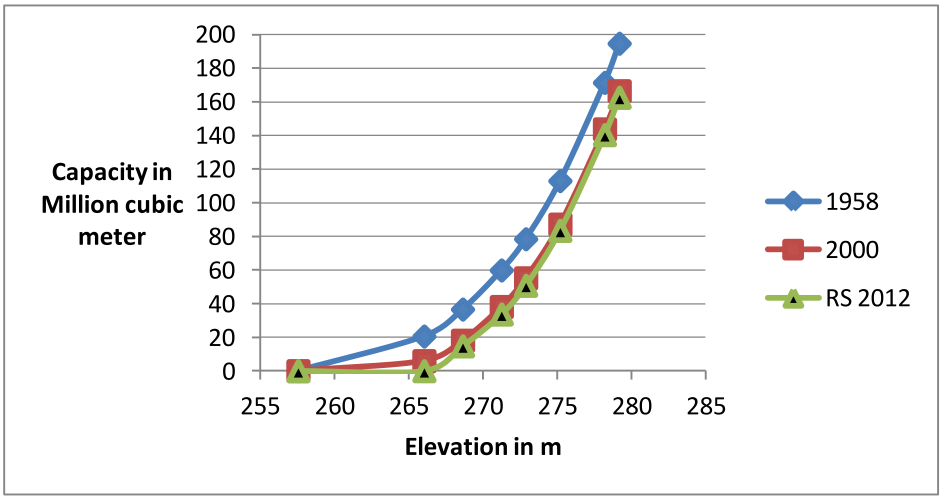

Figure 5. *Comparison of cumulative capacities of Vaigai reservoir for the years 1958, 2000 and 2012*

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Results

Based on the satellite remote sensing studies concerned with Vaigai reservoir, the following results have been concluded. The original capacity of Vaigai reservoir for the year 1958 was 194.785Mm^3. As per the recent survey of 2000, the original live storage capacity of 194.785Mm^3 reduced to 166.533Mm^3 i.e. by 14.50%. Now, the capacity found out in this present study for the year 2012 was 162.620Mm^3. Ultimately, the net sediment deposition between 1958 and 2012 is 32.164Mm$^{3.}$ Average annual silting load per sq.km of drainage area is 2.641x10^{-4} Mm^3/sq.km/year. From the above said results, following inferences can be made.

The gross storage capacity of Vaigai reservoir has reduced from 194.785 Mm^3 to 162.620 Mm^{3}till 2012. Vaigai reservoir has lost its capacity by 32.164 Mm^3 in the year 2012 since its inception, i.e., its total sediment yield is 32.164 Mm^3 which is greater than the sediment yield of the year 2000, which was 28.252 Mm^3. The average annual silting rate for the years 1976, 2000 and 2012 are 8.519%, 14.504% and 16.512% respectively.

Discussion

The net sediment deposition of the reservoir from the year of inception (i.e) 1958 to 2012 is 32.164 Mm^3. From *Table 4*, it is clear that for various elevations, there is change in capacity for different years. Therefore it is understood that definite relationship exists between reservoir shape and the sediment accumulation at various depths since its impoundment (Narasayya et al., 2013). As per the present study, average annual silting rate of vaigai reservoir is increasing day by day and it is 16.512% in 2012. High sedimentation rates were observed where there is steep slope and high rain fall which indicates that sedimentation rate is highly dependent on slope factor and rain fall intensity (Alemaw et al., 2013). If it goes on increasing, it reduces the useful life of the reservoir. Sediment entering the reservoir can be minimized by vegetative treatment and structural intervention. Strong awareness has to be created both for lower land users who are engaged in intense irrigation farming and upper land users for suitable land management practices to protect the water shed (Gelagay and Minale, 2016).

If desilting is proposed the approximate cost will be Rs.238 crores whereas for the construction of new dam, the cost will be Rs.1460 crores. So, the cost of desilting is only 16.20% of the cost of construction of new dam. Hence, to reduce soil erosion, urban development authorities must take environmental preservation measures into account (Park et al., 2011).

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