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Reservoir Capacity Estimation Using Remote Sensing for Bansagar Dam, Madhya Pradesh, India

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ABSTRACT

Reservoir sedimentation caused due to excessive siltation is of immense concern worldwide. It adversely diminishes the capacity for irrigation, power generation, flood moderation, drinking water supply, etc. Regular appraisal of sedimentation rate is desirable for assessing useful life of the reservoir as well as for maintaining optimum reservoir operation schedule. Conventional hydrographic surveys are though more reliable, yet are expensive and time consuming and subsequently, the remote sensing techniques have gained significance. In the present study, remote sensing-based sedimentation study of Bansagar reservoir, a multipurpose river valley project, Madhya Pradesh, India was conducted. Multi-date Indian Remote Sensing (IRS) data covering the water spreads at 1-2 m interval of reservoir levels were analyzed using trapezoidal formula. It is observed that the satellite data inferred reservoir water spread area matched closely with hydrographic survey between and close to Minimum Drawdown Level (MDDL) and Full Reservoir Level (FRL) levels. However, for reservoir water levels much below MDDL, difference between the two techniques were apparent. The remote sensing-based capacity estimate (3449 MCM) showed marginally higher value than original survey (3418.78 MCM), which may be attributed to difference in two approaches.

1. Introduction

Soil erosion, its transportation and subsequent deposition in reservoirs progressively decreases reservoir capacity and consequently, reservoir sedimentation is of great concern to water resource engineers and planners worldwide. The reservoir sedimentation adversely reduces the capacity for irrigation, power generation, flood moderation, drinking water supply, etc. It enhances the risk towards back water levels in head reaches, induces the formation of islands/ deltas and also affects the river regime. The stratification of reservoir due to density current likewise happens in impounded areas of water resources projects. The silting not only happens in the dead storage but it also infringes into live storage capacity, which affects the project functioning and its financial aspects. Therefore, regular appraisal of sedimentation rate is desirable for assessing useful life of the reservoir as well as for maintaining optimum reservoir operation schedule. Recent studies have brought forward distressing evidences on reservoir sedimentation resulting from watershed degradation. The hydrological studies and experiments have predicted that soil erosion in many basins around the world have exceeded the threshold limits and thus the designed capacity of the reservoirs have got reduced due to excessive siltation. These models have helped not only to predict the water yield and but also have been useful to redesign the parameters of hydraulic structures, and also for understanding and to evaluate the anthropogenic and disaster-induced effects on the hydrological regime of a river basin (Naik et al., 2018).

Globally, the water availability from various reservoirs have been declining since the 1980s (Wisser et al., 2013). It is therefore inevitable that many reservoirs will see their capacity substantially hindered by sedimentation prior to arriving at 100 years of age, if suitable remedial measures are not adopted. India's Central Water Commission (CWC, 2015) has published survey data from 243 large reservoirs, out of which, 141 had reduced capacity with a life of approximately 50 years and within this group, 25% had as of now lost over 30% of their original capacity. At 50 sites for which design sedimentation rates were given, 63% of the sites (representing 45% of the storage volume) were experiencing volume loss rates over two times the anticipated rate. The declining reservoir capacity directly undermines our capacity to provide reliable water supplies to both agricultural and urban use, and furthermore meddles with other uses including flood control, hydropower, navigation and fisheries (Annandale et al., 2016). The irrigated regions across the world have expanded five-fold [from 8 million hectares (M ha) to 40 M ha] during the nineteenth century and kept on ascending to 100 M ha by the year 1950 and to a little more than 255 M ha by the year 1995 (Postel 1999). Irrigation is the largest consumer of freshwater. Seckler et al. (1998) have assessed that around 70% of water utilized worldwide every year produces 30 to 40% of the world's food crops on 17% of arable land. In this way, there is a pressing need to manage efficiently the reservoirs, as a saving of a couple of percent can take care of the issues of other water uses, globally (Goel et al., 2007).

It has been assessed that nearly 20 percent of live storage capacity of major and medium reservoirs in India have got silted by the end of twentieth century, which implies a deficiency of water resources availability of around 4 M ha (CWC, 2001). A significant number of reservoirs are losing their capacity at the pace of 0.2 to 1.0 percent, yearly. About 40,000 minor tanks in Karnataka have lost in excess of 50 percent of their capacities. According to CWC (2001), around 6000 M tones of soil are eroded every year in India because of sheet erosion. Besides, gully and ravine erosion annually ravages 8000 ha of productive land. It is therefore imperative to conduct surveys in reservoirs for determining siltation rate and their useful life. This will likewise make information accessible for determining siltation indices for various regions and river basins on which the future design of reservoirs can be formulated (Manavalan et al., 1991). The reservoir capacity surveys additionally help in assessment of loss of capacity besides assessing the effectiveness of soil conservation measures adopted in river valley projects. These studies facilitate the selection of suitable measures for minimizing sedimentation besides the efficient management and operation of reservoirs towards inferring maximum advantages for the society.

Although, reservoir sedimentation survey in India started since 1870, the systematic survey was initiated by Central Board of Irrigation and Power (CBIP) in 1958 with techniques such as boat echo sounder, etc., which are now progressively being substituted with Hydrographic Data Acquisition System (HYDAC). Later, the then Ministry of Agriculture and Irrigation (Department of Irrigation), Government of India had set up a Reservoir Sedimentation Committee on February 4, 1978 to conduct detailed studies and to prescribe policies for minimizing the reservoirs sedimentation leading to their longer life and sustained benefits. Under the eighth Five Year Plan period, CWC started surveys for 144 reservoirs in the country using conventional techniques. The survey outputs reported that the actual rate of sedimentation is more than designed rate of sedimentation in most of the reservoirs (CWC, 2001).

The inflow-outflow and hydrographic survey are the two methods which are usually utilized for the assessment of reservoir sedimentation. The former method involves daily/ hourly measurements of water and sediment inflow/ outflows and is not so precise. The estimations during monsoon period could present numerous difficulties, and there could be several sources of error. The hydrographic surveys are relatively more reliable particularly with present day framework for position fixing and for estimating depth below water surface. Notwithstanding, hydrographic surveys are highly expensive, time consuming and require enormous manpower and sophisticated survey equipment. Hence, it may not be feasible to take up hydrographic surveys, frequently. Ministry of Water Resources (MoWR), Govt. of India has therefore laid the emphasis on the capacity surveys of important reservoirs using remote sensing technique. Present study is carried out to assess sedimentation status and capacity survey by determining the area-capacity curve using multi-date Satellite Remote Sensing (SRS) data. The project objectives are as follows: a) deriving Elevation-Area-Capacity (EAC) curve using SRS and ancillary data, b) Comparison of EAC data derived from SRS and field survey to assess sedimentation status, and c) Assessment of storage loss due to sedimentation, if any.

2. Study Area

Bansagar reservoir is a multipurpose river valley project on Son River situated in Ganga Basin at Deolond, Shahdol District, Madhya Pradesh, India envisaging both irrigation and hydroelectric power generation. The reservoir has a catchment area of around 18,000 sq. km. The location map of the study area is shown as figure 1. The project has been named as 'Bansagar' after *Bana Bhatt*, the renowned Sanskrit scholar of 7th century, who hailed from this region in India. Bansagar Dam is situated at 24º11'30" N latitude and 81º17'15" E longitude. The development work had begun in year 1978 and the project was finally commissioned in year 2006. The Bansagar dam envisages development of a 67 m high and 1020 m long masonry dam including rock fill flanks. The project envisages annual irrigation in Madhya Pradesh (in Rewa, Sidhi, Satna and Shahdol districts) for 2.47 lakh ha m, 1.23 lakh ha m in Uttar Pradesh (in Mirjapur and Allahabad districts) and 1.23 lakh ha m in Bihar towards stabilizing irrigation through old Son canal system. The project is expected to draw power benefits of 425 MW. The Bansagar reservoir falls in Region-2 as per the study carried out by the CWC for 144 reservoirs across the country (CWC, 2001). Figure 2 shows some field photographs of the reservoir and adjoining landscape.

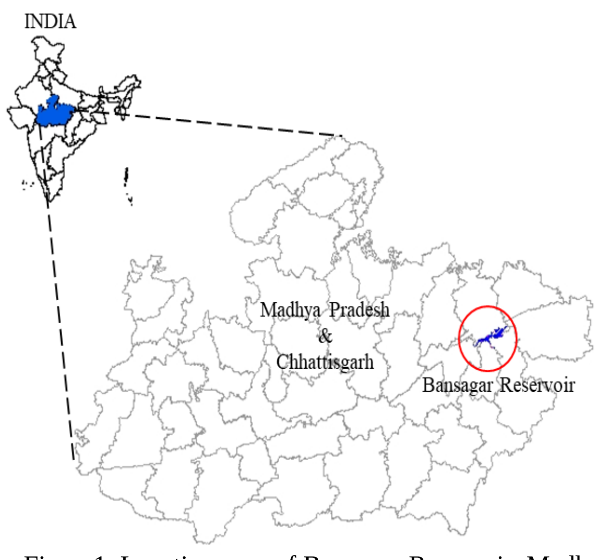

Figure1. Location map of Bansagar Reservoir, Madhya Pradesh, India

a. Synoptic view of Bansagar reservoir and command with agricultural fields located downstream

b. Agricultural fields located downstream along Right Bank Canal (RBC)

c. Upstream (northward) view of Bansagar reservoir showing submergence area

d. Right Bank Canal (RBC) of Bansagar reservoir

Figure 2. Some field photographs of Bansagar reservoir

3. Data Used

Satellite data

The Bansagar reservoir was commissioned during 2006, however impounding took place earlier. While selecting satellite data, the information on various levels achieved after commissioning of reservoir with reference to Minimum Drawdown Level (MDDL) and Full Reservoir Level (FRL) were obtained. However, it was observed that the set of cloud free satellite data at 1-2 m interval pertaining to the period after reservoir commissioning were not available. Hence, some of the satellite data were obtained for the period prior to reservoir commissioning. Table 1 shows the minimum and maximum reservoir levels achieved during 2005-2007. It also shows the difference towards MDDL and FRL corresponding to date of pass of the satellites. Figure 2 shows the satellite data used in the analysis. Multi-date IRS-P6 Resourcesat and IRS-1D LISS-3 satellite data of Path/ Row 101/055 were used in the present study.

Table 1: Operating levels achieved after impounding and/or commissioning of Bansagar reservoir

MDDL (m)	**FRL (m)**	**Levels (m) achieved (Minimum and Maximum during the year)**			**Difference towards FRL (m)***	**Difference towards FRL (m)***
		2007	2006	2005		
323.10	341.64	322.50 m	318.40 m	317.77 m	0.01 m	4.04 m
		334.54 m	337.86 m	328.17 m		

* Corresponding to date of pass of the satellite and reservoir levels on the day

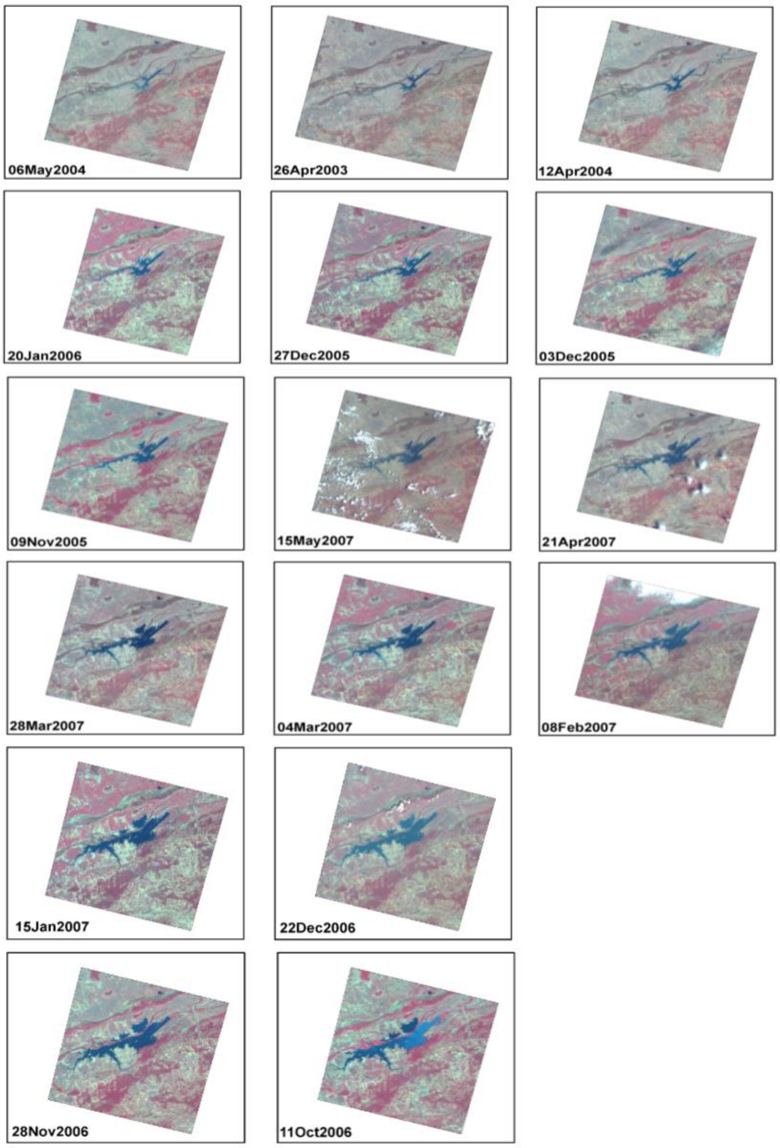

Figure 3. Satellite remote sensing data used in the present study

Field Data

The gauge level data for various satellite passes were obtained from Bansagar Project Authorities (Table 2). The reservoir capacity was analyzed using water spread area using satellite data between MDDL and FRL levels. Additional data were also procured to assess the water spread area below MDDL.

Table 2: Gauge level data for Bansagar reservoir

Sl. No.	Date	Level	Sl. No.	Date	Level
1	06-May-04	312.26	11	10-May-07	326.21
2	26-Apr-03	315.10	12	21-Apr-07	327.55
3	12-Apr-04	316.45	13	28-Mar-07	329.16
4	20-May-06	318.80	14	04-Mar-07	330.36
5	02-Apr-06	319.13	15	08-Feb-07	331.43
6	20-Jan-06	320.62	16	15-Jan-07	333.38
7	27-Dec-05	321.79	17	22-Dec-06	334.90
8	03-Dec-05	323.11*	18	28-Nov-06	335.80
9	09-Nov-05	324.89	19	11-Oct-06	337.60**
10	15-May-07	325.89			

*Corresponding to MDDL

**Corresponding to highest level achieved so far

4. Material and Methods

The Satellite Remote Sensing (SRS) method for reservoir sedimentation assessment is built on the premise that water spread area of reservoir at different elevations continues to diminish because of sedimentation (Narasayya, 2013). In this method, the water spread areas of the reservoir at different levels between FRL and MDDL are computed from satellite images. The difference between areal spread of water between current year and earlier years is the areal extent of silting at these levels. Thus, realizing the reservoir levels (as ground truth) at the time of image acquisition, new elevation-capacity curve could be established and compared with that at the time of dam construction or at earlier survey(s). The changes in the capacity curve will indicate the extent of loss of reservoir capacity. SRS technique yields relatively cost and time effective method for assessing reservoir sedimentation. The manpower requirement is also considerably less, yet the specialized training is desirable. It may be essential to critically compare results of SRS methods with hydrographic survey to establish relative accuracy. The approach for assessment of reservoir capacity using remote sensing usually consists of following steps: a) digital database creation, b) estimation of water-spread area, and c) calculation of capacity.

Previous hydrographic survey

Bansagar dam is a masonry and rock fill dam having FRL at 341.64 m and MDDL at 323.10 m. The reservoir capacity estimation during project conceptualization stage has been worked out from 1:15,840 or 4”=1 mile maps (Source: Bansagar Project Authorities) having contour intervals of 6.1 m (20’) up to R.L. 316.99 m (1040’), 3.05 m (10’) up to R.L. 335.3 m (1100’) and 1.52 m (5’) from R.L. 335.3 m (1100’) to 347.5 m (1140’). The capacity ‘V’ between two successive contours having areas A_1 and A_2 at an interval of ‘h’ has been worked out using modified trapezoidal formula. Table 3 shows the EAC table with water spread areas and capacities for different reservoir elevations. The FRL has been fixed while aggregating the dead storage and lives storage capacity of the reservoir as 0.637 Mha m (0.096 + 0.541) or 5.166 MAF (0.779 + 4.387). This gross capacity was observed to be available at R.L. 341.64 m.

The typical steps followed for reservoir capacity surveys using remote sensing method are as follows: a) procurement of satellite remote sensing data for various passes corresponding to reservoir levels near MDDL to highest levels achieved after commissioning of reservoir (preferred) or since impoundment, b) satellite remote sensing data processing to assess periodical water spread area corresponding to reservoir water levels and estimate live storage capacity thereof, c) preparation of EAC curves (in between near MDDL and highest levels achieved so far and corresponding satellite pass), and d) comparison of EAC data derived from remote sensing and field survey to assess capacity loss and estimation of sedimentation in live storage zone. Figure 3 shows the methodology flow chart for reservoir capacity estimation as used in the present study.

Table 3: Elevation-Area-Capacity table of Bansagar reservoir

Level (m)	Area in Hectares	Capacity (MCM)	Remarks
299.31	0	0	River bed
301.75	202	3	
307.85	733	27	
310.90	1089	49	
313.95	2794	130	
317.00	4555	209	
320.04	8377	403	
323.10	11587	706	MDDL
326.14	15818	1068	
329.18	20838	1679	
332.23	26162	2401	
335.28	32061	3287	
338.33	40457	4386	
341.376	51451	5750	
341.649	51789	6370	FRL

Source: Executive Engineer, Masonry Dam Division, Bansagar Project

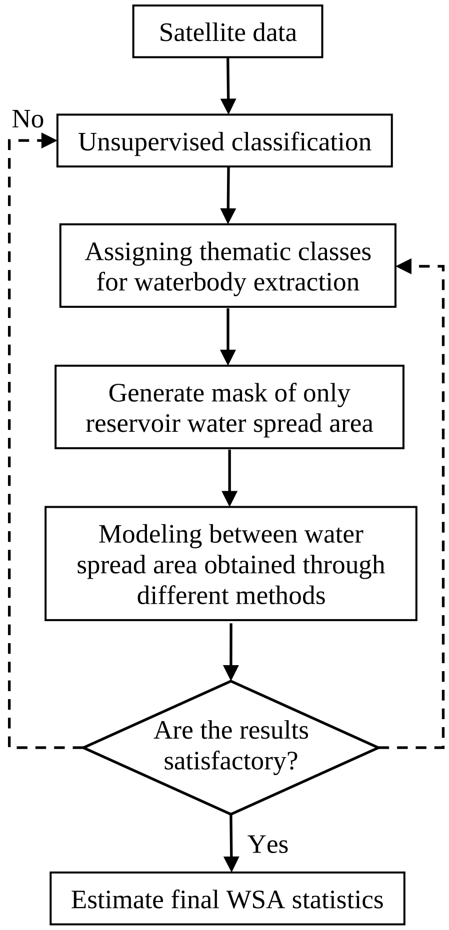

Figure 4. Methodology flow chart for reservoir capacity estimation

Time-series remote sensing data processing

The satellite data was processed to assess reservoir sedimentation based on Digital Image Processing (DIP) techniques. DIP techniques are the utilization of computer algorithms on digital images to infer meaningful information. As multi-date satellite data and other data sources need to be combined and afterwards utilized in a Geographic Information System (GIS) application, it becomes fundamental to have a typical referencing system. Subsequently, multi-date satellite remote sensing data were downloaded and geo-referenced with control points drawn from topographical maps. After geo-referencing of satellite data, image-to-image registration processes were enabled for scenes co-registration.

Estimation of water spread area (WSA)

The reduction in reservoir capacity is governed by decrease in water-spread region at various water levels. Remote sensing data offers a potential tool to estimate water spread area using various DIP techniques such as density slicing, band ratioing, supervised or unsupervised classification techniques, spectral indices, etc. The regions where clear water/land outline exists, the density slicing method is effectively utilized for depiction of water-spread regions. The histogram peaks, minimum and maximum value for water pixels are analyzed for density slicing the images for water bodies extraction. Band ratioing is used for enhancing a particular feature or class from the satellite data. Various spectral indices are available to enhance water, vegetation, soil, etc. The spectral indices such as Normalized Difference Water Index (NDWI) (Gao, 1996), Modified Normalized Difference Water Index (MNDWI) (Han-Qiu, 2005), Normalized Difference Moisture Index (NDMI) (Wilson and Sader, 2002), Automated Water Extraction Index (Feyisa et al., 2014), Water Ratio Index (WRI) (Shen and Li, 2010), Water Extraction Progressive Enhancement Model (WEPEM) (Feng, 2016), General Water Index (GWI) (Yang and Du, 2017), New Water Index (NWI) (Ding, 2009), Normalized Difference Pond Index (NDPI) (Lacaux, 2007), etc. are available for water feature extraction from remote sensing data. Classification techniques such as supervised and unsupervised can be used for the WSA delineation from other features. In supervised classification technique, prior information about the area is available with analyst through ground truth acquisition. This information is fed to the computer through training samples, whose statistics are used for defining the classes. Unsupervised classification technique segments the image into a number of spectral classes and then thematic classes are assigned to these classes. In the present study for the identification of water-spread area using temporal satellite data, the unsupervised classification technique was employed. Various steps adopted for water-spread area estimation were as follows: a) generation of false colour composite (FCC) and analysis of histogram, b) classification, and c) modeling to aggregate identified classes, and d) delineation of water bodies and WSA.

Capacity estimation

Reservoir capacity is estimated at different levels. The areal spread of water body at regular intervals are required while using prismoidal formula and at close interval is needed for trapezoidal formula. A curve fitting is done between elevation and the area values obtained from the satellite analysis. The volume is then estimated by either of the formulae as given below:

Trapezoidal formula –

$$V = \Sigma\, h/2\, (A_1 + A_2) \quad ...(1)$$

Cone formula or modified trapezoidal formula-

$$V = \Sigma\, h/3\, [A_1 + A_2 + SQRT\,(A_1 * A_2)] \quad ...(2)$$

Prismoidal formula –

$$V = \Sigma\, h/3\, (A_1 + 4A_2 + 2A_3 + 4A_4 + \ldots\ldots.) \quad ...(3)$$

Where 'h' is the height between two successive water levels. 'A_1' and 'A_2' are the areas at successive water contours.

Comparison with hydrographic survey

In order to estimate the capacity loss, the cumulative capacity of reservoir is estimated by adding the capacities between different water level zones. This cumulative capacity is compared with the capacity either from original EAC curve generated at the time of construction of reservoir or with the capacities previously calculated. The changes in capacity provides the overall loss due to sedimentation.

5. Result

The Indian Remote Sensing (IRS) multi-spectral satellite data for various dates of passes were classified while following unsupervised classification approach. Various input and statistical parameters were set iteratively for classification of water bodies such that ambiguities with land surface features were minimized. At tail water levels, some ambiguities with other features were observed, which were handled interactively while controlling it with elevation information obtained from project authorities corresponding to villages coming under submergence at various reservoir levels and falling in close proximity along original river course.

Reservoir water spread area

It was observed that satellite data derived reservoir water spread area matched closely with hydrographic survey between and close to MDDL and FRL levels. The difference between the two techniques were much evident for reservoir water levels much below MDDL. As the endeavour in the present study was to assess the reduction in live storage capacity, hence water spread area information below MDDL were not used to assess capacity loss with respect to field survey. Figure 2 shows the IRS satellite data covering the Bansagar reservoir and water spread area at various reservoir levels. Figure 5 and table 4 shows figuratively and tabulated data of reservoir water spread area at various elevation levels. Figure 6 shows the reservoir water spread area at various levels.

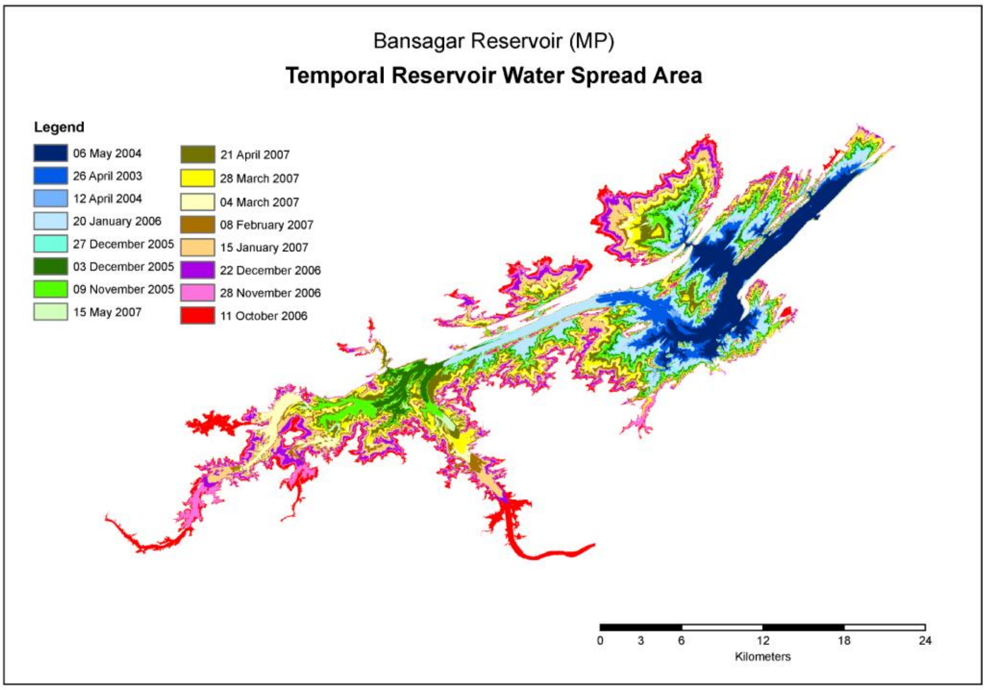

Figure 5. Reservoir water spread area at various levels

Table 4: Reservoir water spread area at various levels and date of passes

Date	Level (m)	Area (ha)
06-May-04	312.26	3671.358
26-Apr-03	315.1	5620.58
12-Apr-04	316.45	6072.983
20-Jan-06	320.62	9403.271
27-Dec-05	321.79	10432.67
03-Dec-05	323.11	12259.07
09-Nov-05	324.89	14660.69
15-May-07	325.89	15572.57
21-Apr-07	327.55	18611.27
28-Mar-07	329.16	21217.89
04-Mar-07	330.36	23262.54
08-Feb-07	331.43	24968.77
15-Jan-07	333.38	28823.92
22-Dec-06	334.9	31735.38
28-Nov-06	335.8	33838.35
11-Oct-05	337.6	38560.3

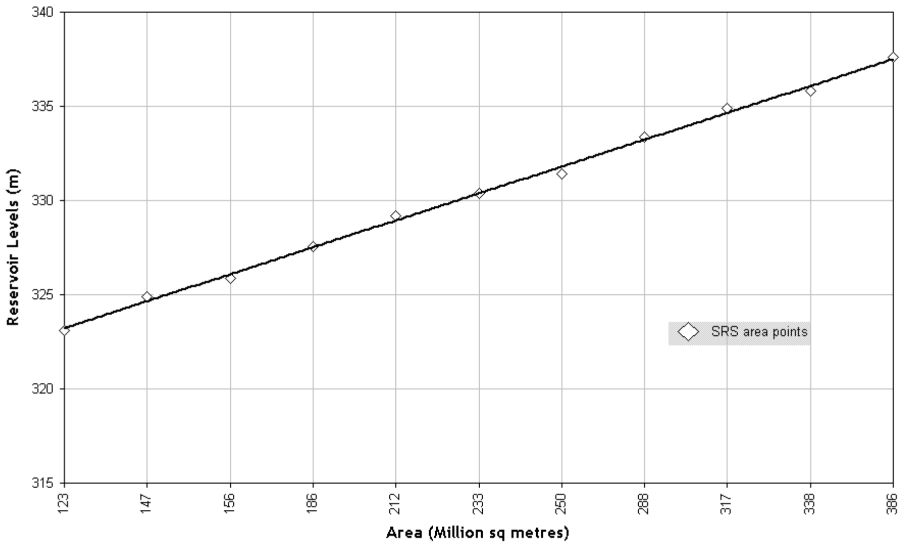

Figure 6. Reservoir water spread area at various levels

Calculation of reservoir capacity

Computation of reservoir capacity at different elevations has been made while following Cone formula or Modified Trapezoidal formula (equation 2). Figure 7 and Table 5 shows the elevation-capacity data drawn from satellite remote sensing based methods. The multi-date satellite remote sensing data was used to assess capacity and capacity loss due to sedimentation in Bansagar reservoir. The reservoir was impounded during the year 2002 and formally commissioned during year 2006. The original capacity estimation was done following trapezoidal method and hence, same method was deployed to assess capacity at various elevation levels and reduction in capacity as attributed to sediment deposition in various reservoir zones. Table 5 shows the cumulative live storage capacity estimated at various reservoir zones. The two capacity estimates (original and remote sensing based) have close correspondence. The remote sensing based capacity estimate (3449 MCM) showed slightly higher value than original survey (3418.78 MCM), which may be attributed to difference in two approaches. The difference is insignificant (less than 1%) and only re-affirms the live storage estimation made by field survey.

Table 5: Elevation-capacity data (Trapezoidal method)

Sl.No.	Date of pass	Reservoir levels (m)	Original live capacity (MCM)	Remote sensing based Capacity (MCM)
1	03-Dec-05	323.11	131.89	149.60
2	09-Nov-05	324.89	211.03	239.27
3	15-May-07	325.89	329.59	390.41

4	21-Apr-07	327.55	643.85	673.76
5	28-Mar-07	329.16	966.82	994.16
6	04-Mar-07	330.36	1250.94	1260.95
7	08-Feb-07	331.43	1504.50	1518.93
8	15-Jan-07	333.38	2029.10	2042.96
9	22-Dec-06	334.90	2470.81	2503.03
10	28-Nov-06	335.80	2769.79	2798.06
11	11-Oct-05	337.60	3418.78	3449.19

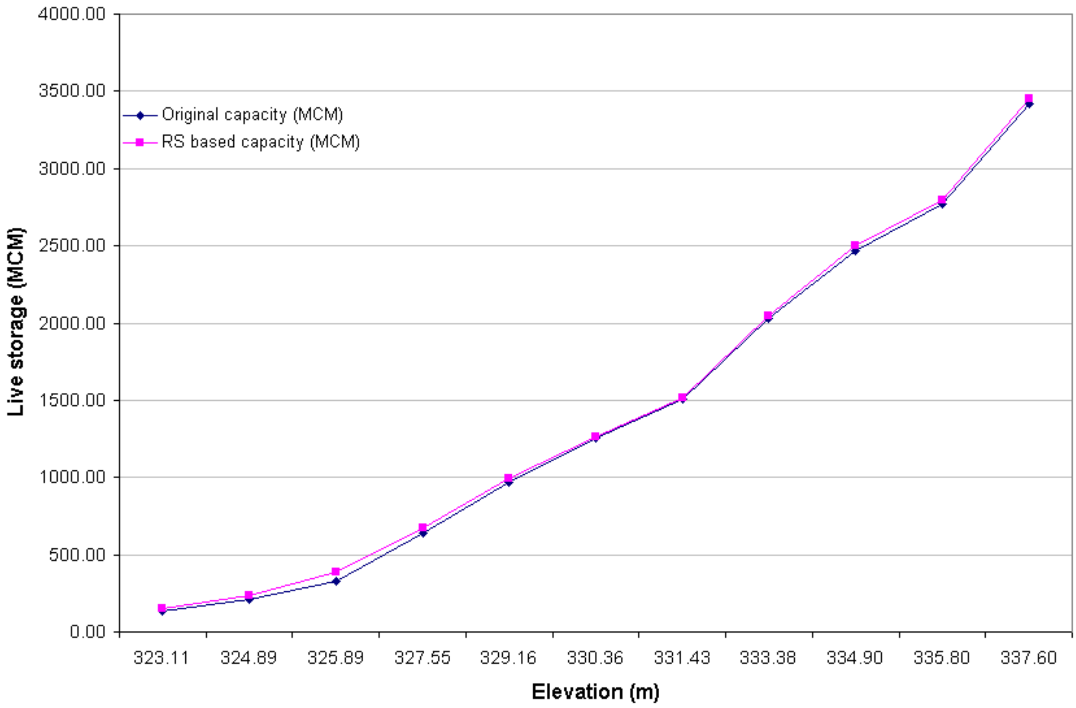

Figure 7. Comparison of capacities (original and remote sensing based)

Limitations of SRS Techniques

Although, satellite remote sensing based survey of reservoir water spread area and storage estimation has several advantages over conventional methods yet it has certain limitations such as- a) Hydrographic survey below MDDL may be essential to estimate changes below MDDL, b) Less but specialized manpower required along with availability of image processing software, c) Special care required at land and water interface to distinguish water pixels, d) SRS techniques can give relatively accurate estimates for large size fan shape reservoirs, which show large change in area for small change in water levels. Thus, for elongated shape reservoirs with V or U shape valley with steep banks, the accuracy of method will reduce. With steep/ vertical banks for elongated reservoirs, the changes in reservoir widths may be smaller and sometimes it may not be possible to estimate changes in the water spread boundary, if these changes are larger than the resolution or pixel size then only computations will be reasonable, and e) In SRS techniques, there is need to separate the water area in extended tail and the main river channels where water level could be higher than this reservoir level. This will also need some experience and insight into the reservoir under flood conditions.

6. Conclusion & Recommendations

The present study on sedimentation status of Bansagar Reservoir using remote sensing techniques was carried out to assess the reservoir water spread area and corresponding capacities at different reservoir levels. Since, the major cause of reduction in storage capacity is sediment deposition, the reservoir sedimentation surveys by remote sensing and hydrographic technique should be periodically carried out. The present study concludes that two capacity estimates (original and remote sensing based) have close correspondence. The remote sensing based capacity estimate (3449 MCM) showed slightly higher value than original survey (3418.78 MCM), which may be attributed to difference in two approaches. The difference is insignificant (less than 1%) and only re-affirms the live storage estimation made by field survey.

Recommendations

The working group for reservoir sedimentation assessment under National Natural Resources Management System, Standing Committee, Water Resources (NNRMS-SC-W) has given certain recommendation for reservoir sedimentation studies (CWC, 2001). CWC has suggested that the reservoir sedimentation survey should be carried out every 5th year by SRS technique and every 15th year by conventional hydrographic method. The norms and guidelines as set by Indian Standard Organization (ISO) and United States of Bureau of Reclamation (USBR) for Reservoir Sedimentation Assessment (ISO/DIS 6421 – Draft): Hydrometric determination test methods for measuring sediment accumulation in reservoirs-recommends that Bathymetric surveys should be carried out after flood season if variation in total reservoir capacity exceeds by 3% to 5%. Such recommendations on the frequency of reservoir sedimentation surveys using satellite remote sensing and hydrographic methods are governed by number of factors such as: a) extent of possible error in given measurement technique, b) frequency of high floods and duration of dominant discharge responsible for major sediment transport, c) high rates of siltation, which dictate frequent updating of reservoir survey, d) age of reservoir and e) reservoir size and catchment characteristics.

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