Assessment of Reservoir Sedimentation Using Remote Sensing Satellite Imageries

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Abstract

The Satellite Remote Sensing (SRS) method for assessment of reservoir sedimentation uses the fact, that the water spread area of reservoir at various elevations keeps on decreasing due to sedimentation. Remote Sensing technique gives us directly the water-spread area of the reservoir at a particular elevation on the date of pass of the satellite. This helps us to estimate sedimentation over a period of time. This paper describes assessment of sedimentation carried out for the Srisailam Reservoir using Remote Sensing satellite imageries. The area capacity curve of year the 1976, when actual impoundment was started, is used as a base for sedimentation assessment for the year 2004. The results of Remote Sensing survey for the period 2001-04 are compared with the deposition pattern of Srisailam Reservoir with the standard types of deposition pattern as per Area Reduction Method suggested by Borland and Miller. The sediment index computed considering total sediment deposition since 1976 to 2004 comes to around 543.84 t/m²/year which is lower than the rates suggested by Garde & Kothari.

Key words: Satellite Remote Sensing, Images, NDWI, IRS P6, Sediment, Thresholding.

1. Introduction

A reservoir will generally be located towards the end of a large watershed and receive inflows from major rivers (Jørgensen 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). Therefore, capacity surveys are important for proper allocation and management of water in a reservoir. Knowledge about the quantum of sediment and its deposition pattern in various zones of a reservoir is very essential to assess the balance life of reservoir. In view of this, systematic capacity surveys of a reservoir should be conducted periodically. 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. Remote Sensing technology, offering 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. Reservoir water spread area 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. This when integrated over a range of elevations using multi-date satellite data enables in computing volume of storage lost due to sedimentation. In this paper satellite imageries were analysed to assess sedimentation in Srisailam Reservoir in Andhra Pradesh state of India. Attempts were made to compare the results with erosion rates suggested by Garde & Kothiyari.

2. Literature Review

A Geographical Information System (GIS) can be used to model bathymetry and the spatial distribution of sediments (Evans et al., 2002; Heimann, 1995). The use of Remote
Sensing technique to estimate suspended sediment has been reported by several investigators (Solomonson, 1973; Bartoluci et al., 1977; Holeyer, 1978; Khoram, 1981). Smith et al. (1980) determined siltation in the Aswan High Dam Reservoir by comparing reflectance values in the green and red portions of the spectrum. Research findings indicate that siltation during the flood period was largely confined to the main river channel of the reservoir and large embayments. Areas of extensive siltation were identified and the amounts of deposition were determined through ground surveys. This information was used to predict the distribution of silt deposits in the reservoir. Rao et al. (1985) used a visual interpretation technique on large scale imagery of Landsat-MSS to estimate the water-spread area at different levels to evaluate the capacity of the reservoir and concluded that the results are comparable with hydrographic survey observations and similar to the curves obtained from the conventional methods. A digital technique in which density slicing of Landsat-MSS Near-infrared (NIR) data was performed for extracting the water-spread area and correlated computed reservoir capacity based on the surface area obtained using cone formulae. Goel & Jain (1996) earned out a reservoir sedimentation study using the density-slicing approach for water-spread area extraction. The status of studies shows that there is lot of scope of the Remote Sensing approach for sedimentation assessment in the Western Ghats region, which has extensive areas that are prone to soil erosion. The assessment may be performed on the basis of geomorphic analysis and modelling in combination with analysis of recent bathymetry to determine the historical pattern and rate of deposition (Gregory L.Morris, Jiahu Fan, December 2010).

The shape of the reservoir is defined by the depth to capacity relationship. The Borland and Miller method, also known as the Area-Reduction Method, was developed from resurvey data of 30 US reservoirs. The Empirical Area-Reduction Method has been developed with revisions by Lara and subsequent changes by Pemberton. Rooseboom and Annandale used field survey data for 11 large reservoirs in South Africa to compile a semi-empirical graph. Their new technique represents new empirical curves based on variation of wetted-perimeter through the reservoir length for predicting longitudinal sediment distribution pattern in reservoirs. Among the scientists who implemented the Rooseboom and Annandale method, Michalec and Tarnawski (2006) studied the possibility of application of this method. They showed that supplementary research works on additional parameters considering the reservoir shape is still required. Also, Mohammadzadeh and Heidarpour introduced a new empirical method for prediction of sediment distribution in reservoirs based on original area-capacity and depth-capacity data of reservoirs.

3. Methodology

The detailed methodology explained in the form of flow chart is given blow.

FLOW CHART FOR METHODOLOGY OF SRS TECHNIQUE

The Satellite Remote Sensing (SRS) method for assessment of reservoir sedimentation uses the fact, that the water spread area of reservoir at various elevations keeps on decreasing due to sedimentation. These water spread areas of the reservoir at different levels between Full Reservoir Level (FRL) and Minimum Draw Down Level (MDDL) in different months of the year could be computed from satellite imageries. Knowing the reservoir levels (as ground truth) on date of pass of the satellite, Elevation-Capacity curves could be established and compared with that at the time of impoundment of reservoir. Shift in the capacity curve will indicate extent of loss of reservoir capacity.

4. Study Area: Srisailam Reservoir

Srisailam Reservoir (Figure 1) subsequently renamed as Neelam Sanjeeva Reddy Sagar (NSRS) located in Nandikotkur taluka of Kurnool District of Andhra Pradesh State of India is selected for assessment of sedimentation using Remote Sensing. The Srisailam Dam is located in a narrow gorge of Krishna valley with water standing always for about 16 m depth in the deep course of the river. The project is situated about 869 km down stream of the origin of the river Krishna at Mahabaleshwar in the Western Ghats. The dam up to 252.98 m elevation (above Mean Sea Level) was constructed in 1976, when part impounding of the reservoir was commenced. The gates were erected and water was stored upto FRL from 1984. The FRL and MDDL of Srisailam Reservoir are 269.748 m and 243.84 m respectively. The catchment area of the reservoir is 2,06,030 km².

5. Data Used

Topographical Data
3. Field Data

Maximum, minimum and daily water level data for the period from 1984 to 2004 were collected from the dam site. The salient features of the reservoir along with the original Area-Elevation-Capacity curve for the year 1976, catchment area details, land use patterns, and maps were also collected from the Irrigation & Command Area Development department of Andhra Pradesh.

4. Satellite Data

The multi-spectral data from IRS 1C, 1D, and IRS P6 Satellites for LISS-III Sensor are available for the cloud free dates at different selected levels for the year 2001-04 were used for this study. The Srisailam reservoir water spread was covered in one scene of Path-100, Row-61 for IRS 1C, 1D, and IRS P6.

6. Analysis of Satellite Imageries

After comparing the availability of cloud free imageries for different dates of pass vis-a-vis water level variation for different dates collected from the dam site, it was observed that there were very few imageries for a single water year during which there was maximum fluctuation in reservoir water levels. Therefore, the imageries for the period 2001-04 were collected for cloud free dates in order to show variation from near FRL to MDDL. Cloud free imageries below MDDL were not available, hence the analysis of field data was restricted to the live storage zone only.

The capacity estimation of Srisailam Reservoir using Remote Sensing technique was carried out for the year 2004 in order to know deposition of sediment since 1976 in the reservoir. The area capacity curve of 1976 (Figure 2) is thus taken as a base for the present study. The results of the hydrographic survey (1997) is also compared with the present Remote Sensing survey. The satellite data was obtained from National Remote Sensing Centre (NRSC), ISRO, Bangalore.
Sensing Centre (NRSC), Hyderabad, Andhra Pradesh state of India. The data was then imported in the Digital Image processing software EASI/PACE (Engineering Analysis and Scientific Interface/Picture Analysis Correction and Enhancement) v7.1. The EASI/PACE software directly reads the IRS 1C, 1D and IRS P6 raw imageries. On visual analysis, the pixels representing water-spread area (except at the periphery) of the reservoir were quite distinct and clear in the False Color Composite (FCC) image. The reservoir area and its surroundings (area of interest) were separated out from the full scenes from all the images. These imageries were geo-referenced using SOI toposheets. All images were geometrically corrected and transformed into the standard cartographic projection and scale so that any measurement made on the image will be accurate with those made on the base map and ground. The geometric corrections enable the images to be represented in their latitudinal and longitudinal coverage. For geo-referencing, clearly identifiable features like crossings on Krishna River, sharp bends in the rivers & drains, bridges etc. were selected as Ground Control Points (GCP’s). Root Mean Square Error (RMSE) of less than 0.05 was ensured. As this is the first step in geo-coding, it needs to be precisely done, as the accuracy of result is totally dependent on the accuracy of the base map. In present study, imagery of 16th October 2004 was first geo-referenced, since this was very sharp, clear, noise free and cloud free and it was considered as the base imagery. The imageries of other dates were geo-referenced with this base imagery.

7. Digital Image Processing for Delineation of Water and Land Boundary

For delineating the land and water pixels following two methods were adopted for a better accuracy.

Generation of Contours

Contours of equal intensity (lines of equal digital numbers) were generated on the image. Contours which showed probable water-land delineation were extracted and edited based on Digital Number (DN) of various bands. The contour satisfying the condition $DN_{NIR} < DN_g < DN_{IR}$ (NIR:Near Infrared, R:RED, G:GREEN) at maximum number of pixels on the contour, is considered as final contour giving delineation representing water spread area at that particular elevation. This final contour is then further edited for corrections.

Thresholding Technique

After analyzing the histogram of the image, the ranges of NIR band for land/water boundary demarcation were identified. The NIR band was thresholded into two to three ranges. First range contained all confirmed water pixels and a mask was created, second and third range contained pixels at the land/water boundary and at the tail portions of the water-spread extending into river course and masks were created accordingly. These range masks were evaluated for the correctness of range limits by consulting FCC. In most of the cases, the criterion for thresholding the image could not give satisfactory results in identifying the correct water pixels due to shallow depth of water at some of the locations along the periphery and at the tail portion of the reservoir. Hence, actual water pixels in these two range masks were estimated by including thresholding of RED band data and further applying the condition of reflective property of water for NIR and RED band. (The reflectivity of water in NIR band is smaller than RED band and hence the DN values of NIR band will be smaller than DN values of RED band for water). The total reservoir water spread area was estimated by adding the water spread masks under the different range masks. Accurate delineation of water and land boundary is achieved by Thresholding Technique and the following methods were adopted.

Water Index (WI) Method

The water pixels are identified by taking band ratio of Green/Near Infrared. Since the maximum absorptance of Electromagnetic Radiation by water is in the Near Infrared (NIR) spectral region, the DN value of water pixel in NIR band is appreciably less than the DN values of Green spectral region, which is having high reflectance value. This ratio separates the water body from soil/vegetation quite distinctly.

Modified Normalized Difference Water Index (NDWI) Method

The condition used to separate the water pixels from the other pixels is as follows:

$$NDWI = \frac{(DN_g - DN_{NIR})}{(DN_g + DN_{NIR})} \quad \text{…….. (i)}$$

“If NDWI is positive and if the DN value of NIR band is less than the DN value of Red band and the Green band (NIR<RED<GREEN), only then the pixel must be classified as water”.

8. Corrections in Vector Contours and Masks

Water in tail channels of Srisailam Reservoir appears as a part of reservoir in the imagery however, the elevation of the water surface in these river channels remains higher than the water surface elevation of the reservoir. This extended tail of main river channel and tributaries with higher water surface elevation were cut at the point of termination of reservoir water spread at corresponding levels taking help of base map (contour map). The longitudinal section of main river and tributaries proved to be useful in order to decide cut-off points. Removal of extended tail is very much necessary as this could generate considerable errors in estimation of water-spread areas.

In the masks, isolated water pixels within and near the periphery of the reservoir, which show no hydraulic connectivity were removed. Similarly, water pixels downstream of reservoir were not a part of reservoir, hence
were removed. The areas of islands present in the reservoir were deducted from the total water spread area from all the imageries.

After applying corrections, the actual water spread areas were obtained. The water spread areas of the reservoir extracted from imageries of 2001 to 2004 at different elevation are shown as Figure 3. Estimated water spread areas for different dates (dates of satellite over pass) obtained by digital analysis of satellite data corresponding to different elevations as shown in Table-2 were used to generate new Area-Elevation curve.

9. Estimation of Cumulative Capacity

The reservoir capacity between two elevations of Srisailam Reservoir was computed by following Prismsoidal Formula using water spread areas at corresponding elevations obtained above:

\[ \Delta V_{1-2} = \Delta h \left( \frac{A_1 + A_2 + \sqrt{A_1 A_2}}{3} \right) \]  

Where, \( \Delta V_{1-2} \) = Volume between elevation \( E_2 \) and \( E_1 \) (\( E_2 > E_1 \))

\( \Delta h = E_2 - E_1 \)

\( A_1, A_2 = \) Water spread areas at elevation \( E_1 \) and \( E_2 \)

Figure 3. Water Spread Areas at Different Elevations for Srisailam Reservoir.
The cumulative capacities computed at different elevations shown in Table-1 were plotted against corresponding elevation in order to generate new Elevation-Capacity curve as shown in Figure 4.

### 10. Results and Discussions

The Elevation-Capacity curves for the year 2004, as well as original (1976) and intermediate survey (1997) are shown as Figure 4. The shift in capacity curves as compared to original capacity curve represents the loss in capacity or sediment deposited at different levels in live storage zone. It was observed that the capacity of the reservoir is reduced to 6764.04 Mm³ from 8724.882 Mm³ in 2004. The sediment index thus computed considering total sediment deposition of 1960.842 Mm³ since 1976 upto 2004 (28 years) and taking 2,06,030 km² catchment area comes to around 339.90 m³/km²/year which is equivalent to 543.84 T/km²/year which is close to the sediment index of 600 to 700 T/km²/year indicated in iso-erodent map of Garde and Kothyari (1990).

An attempt was also made to compare the sediment deposition pattern of Srisailam Reservoir for the year 1997 and 2004 with the four standard sediment deposition patterns suggested by Borland and Miller. This comparison is shown vide Figure 5. Out of four types of reservoirs classified by Borland & Miller (1958), Srisailam Reservoir falls in Type-I i.e Lake Type as per original capacity depth relationship of

![Figure 4. Comparison of Cumulative Capacities of Srisailam Reservoir for Different Years.](image-url)

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Date of Satellite Pass</th>
<th>Observed WL (m)</th>
<th>Elevation Difference (m)</th>
<th>Area (Mm²)</th>
<th>Cumulative Capacity (Mm³)</th>
<th>Loss in Cumulative Capacity (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MDDL</td>
<td>243.840</td>
<td>0.000</td>
<td>91.135</td>
<td>66.631</td>
<td>56.401</td>
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<tr>
<td>2</td>
<td>2-Jan-2004</td>
<td>245.525</td>
<td>1.685</td>
<td>106.174</td>
<td>73.096</td>
<td>55.692</td>
</tr>
<tr>
<td>3</td>
<td>25-Dec-2002</td>
<td>247.175</td>
<td>1.650</td>
<td>120.889</td>
<td>81.784</td>
<td>63.213</td>
</tr>
<tr>
<td>7</td>
<td>18-Feb-2001</td>
<td>261.090</td>
<td>3.900</td>
<td>329.366</td>
<td>292.212</td>
<td>245.634</td>
</tr>
<tr>
<td>8</td>
<td>3-Dec-2004</td>
<td>263.550</td>
<td>2.460</td>
<td>395.436</td>
<td>350.773</td>
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<tr>
<td>9</td>
<td>24-Nov-2004</td>
<td>264.350</td>
<td>0.800</td>
<td>419.705</td>
<td>372.752</td>
<td>351.794</td>
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<td>11</td>
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<td>1.373</td>
<td>615.184</td>
<td>541.800</td>
<td>550.644</td>
</tr>
</tbody>
</table>

Table 1. Capacity Loss Estimation due to Sedimentation in Srisailam Reservoir for Different Years
1976. After carrying out Remote Sensing survey for the year 1997 & 2004 it could be seen in Figure 5 that sediment deposition was close to the Type-I both in 1997 & 2004.

11. Conclusions

The gross, dead and live storage capacities of Srisailam Reservoir for the year 1976 were 8724.88 Mm³, 1557.68 Mm³ and 7167.2 Mm³ respectively. As per recent Remote Sensing survey of 2004, it was observed that the original live storage capacity of 7167.20 Mm³ was reduced to 5467.54 Mm³ i.e. by 23.714% in 28 years. Thus, the average annual rate of loss of live storage capacity worked out to 0.846%. In addition to these the rate of percent annual loss of live capacity appears to be in line with annual loss of 0.5 to 1.0% in many of the Indian Reservoirs. The sediment index computed considering total sediment deposition 1960.842 Mm³ since 1976 upto 2004 (28 years) works out to 543.84 T/ km²/year which is close to value of 600 to 700 T/ km²/year indicated in iso-erodent map of Garde and Kothyari (1990). The comparison of deposition pattern of Srisailam Reservoir with the standard types of deposition pattern suggested by Borland and Miller indicated that the sediment deposition pattern in Srisailam Reservoir also followed Type-I in 2004. The data indicates that a definite relationship exists between the reservoir shape and the percentage of sediment accumulated in various depths since its impoundment.

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