ASSESSMENT OF RESERVOIR SEDIMENTATION USING REMOTE SENSING

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Periodic evaluation of sediment deposition pattern and the assessment of available live storage capacity in a reservoir are an integral component of the optimum water resources management. The conventional techniques of sedimentation quantification in a reservoir, like the hydrographic surveys and inflow-outflow methods, are cumbersome, costly and time consuming. Further, prediction of sediment deposition profiles using empirical and numerical methods requires large amount of data and the results are still not accurate.

Remote sensing, through its spatial, spectral and temporal attributes, can provide synoptic, repetitive and timely information regarding the revised water spread area in a reservoir. By using the digital analysis techniques and the geographic information system in conjunction, the temporal change in water spread area is analysed to evaluate the sediment deposition pattern in a reservoir. A case study, related to the assessment of sediment deposition in Bhakra reservoir, Gujarat State, India, using remote sensing technique, is presented. The data of IRS-1B LISS-II sensor is used and the analysis is performed on the ERDAS/IMAGINE system.

1.0 Introduction

Soil is eroded due to rainfall and winds, resulting in tremendous sediment movement into watercourses by flood and storm waters. A great amount of sediment is annually carried by the Indian rivers down to the reservoirs, lakes, estuaries, bays, and oceans. The impact of sediment erosion, transport and deposition is widespread. Deposition of coarse sediments reduces the reservoir storage and channel conveyance for water supply, irrigation, and navigation and causes extensive disturbance to streams. Suspended sediments reduce water clarity and sunlight penetration, thereby affecting the biotic life. As the sediment settles to the bottom of water bodies, it buries and kills vegetation and changes the ecosystem.

A number of river valley projects have been constructed in India for serving various conservation purposes, like water supply for domestic and industrial purposes, irrigation, hydropower generation, navigation and recreation. One of the principal factors, which threaten the longevity of such projects, is the accumulation of sediments in the reservoirs. Sedimentation reduces the storage capacity of reservoirs and hence their ability to conserve water for various intended purposes. Sedimentation also reduces the survival of aquatic species and restricts the use of water for multiple purposes. It further increases evaporation due to increase in the exposure area of water.

In order to determine the useful life of a reservoir, it is essential to periodically assess the sedimentation rate in a reservoir. With the correct knowledge of the sedimentation processes going on in a reservoir, remedial measures can be undertaken well in advance and reservoir operation schedules can be planned for optimum utilisation of water. Most common conventional techniques for sedimentation quantification are a) direct measurement of sediment deposition by hydrographic surveys and b) indirect measurement of sediment concentration by inflow - outflow method. Both these methods are laborious, time consuming, and costly and have their own limitations. Sampling and measurement of suspended sediments is a tedious and expensive program for either in-situ or laboratory work.

With the introduction of remote sensing techniques in the recent past, it has become very cheap and convenient to quantify sedimentation in a reservoir and to assess its distribution and deposition pattern. Remote sensing techniques, offering data acquisition over a long time period and broad spectral range, are superior to conventional methods for data acquisition. The advantage of satellite data over conventional sampling procedures include repetitive coverage of a given area every 16/22 days, a synoptic view which is unobtainable by conventional methods, and almost instantaneous spatial data over the areas of interest. The remote sensing techniques provide synoptic view of a reservoir in a form very different from that obtained with surface data collection and sampling.

2.0 Sedimentation Assessment Using Remote Sensing

Multi-temporal satellite data are extremely useful in determining sedimentation rate in a reservoir. Advantages of using remote sensing data is that it is highly cost effective, very easy to use and it takes little time in analysis as compared to conventional methods.

Methodology

In India, more than 80% of the annual rainfall occurs during four monsoon months from June to September. Hence, water level in a reservoir can be expected to be at a higher elevation after the monsoon season (September/October) before it gradually depletes to lower levels towards the onset of next monsoon (May/June).

For the quantification of volume of sediments deposited in the reservoir, the basic information extracted from the satellite data is the water spread areas in a reservoir at different water surface elevations. With the deposition of sediments in reservoir submerged area, the contour area at any elevation decreases. Greater deposition of sediments at an elevation causes greater decrease in the contour area. The original contour areas at different elevations and the original elevation-area-capacity curves at the dam site can be obtained from the original capacity surveys, which are carried out before the planning and construction of a dam. Revised contour areas, after the process of sedimentation, can be taken as the continuous water spread area of the reservoir at the elevation of water surface. Using the synoptic satellite data and the image interpretation techniques, the water-spread area of the reservoir at the instant of satellite overpass can be determined. In this way, revised contour areas can be calculated and the revised elevation-area curve can be prepared.

The reduction in reservoir capacity between consecutive contour levels is computed using the prismoidal formula. The overall reduction in capacity between the lowest and the highest observed water levels can be obtained by adding the reduced capacity at all levels. Water levels in the reservoir corresponding to the date of imagery and time of satellite pass can be obtained from the dam authorities. It is important to mention here that the amount of sediments deposited below the lowest observed level can not be determined using remote sensing data. Hence, the volume of reservoir below the lowest observed level is assumed to be the same before and after the sedimentation. Because of this reason, the actual sedimentation rate is always higher than that determined using remote sensing technique. However, if accurate results are required, then the hydrographic survey for the region below the lowest observed water spread area can be carried out.

Selection of Period of Analysis

This is an important step in carrying out the analysis for reservoir sedimentation assessment using remote sensing data. The pertinent information, which is extracted from the remote sensing data, is the water spread area at different dates of pass of the satellite over the reservoir area. Though in the wavelength region 0.45 - 0.52 □m, the information within 1 - 2 m depth below the water surface (like sediment concentration, shallow water depth etc.) can be obtained, it can not be used to quantify the amount of sediment deposited in the reservoir. Therefore, it is imperative to use the remote sensing data of such a period when there is maximum variation in the elevation of the reservoir water level.

Temporal remote sensing data for any water year can be selected and analysed. However, if the historical records of maximum and minimum water level in each year are available, the water year of maximum variation is a better selection for sedimentation analysis. A wet year followed by a dry year is the best period for such type of study since for such sequence, the reservoir water level is likely to fluctuate from the maximum to the minimum level. The remote sensing data series of the same water year or continuous water years must be selected in sequence to the extent possible. The availability of the satellite data and its cost are additional factors, which govern the selection of period of analysis. In general, sedimentation assessment must be made for major reservoirs after a gap of 5 to 10 years.

Selection of Suitable Satellite and Sensor

A number of satellites are available for acquiring remote sensing data and the most common among them are listed below along with their sensors and spatial resolution:

a) IRS - 1A/ IRS - 1B [LISS-I (72.5 m) & LISS-II (36.25 m)]
b) IRS - 1C [PAN (5.8 m) & LISS-III (23.5 m)]
c) LANDSAT [MSS (80 m) & TM (30 m)]
d) SPOT [PAN (10 m) & spectral (20 m)]

Multi-spectral information is required for the identification of water pixels and for differentiating the water pixels from the peripheral wet land pixels. It is also desirable to use the data of higher resolution for obtaining accurate results. However, the use of PAN sensor data is not usable because it lacks spectral information. IRS-1C satellite was launched in the year 1995. Though the LANDSAT and SPOT satellites have better resolution than IRS satellites, the difference is only marginal while the cost of their data is comparatively very high. At present, the remote sensing data of indigenous IRS satellites is the best selection from the cost and resolution considerations.

Identification of Water Pixels

The basic output from the remote sensing data analysis is the water spread area of the reservoir. The two techniques of remote sensing interpretation, i.e. visual and digital, can be used for water spread delineation. Visual techniques are based purely on the interpretive capability of the analyst and it is not possible to use the information of different bands, after the visual product is generated. Around the periphery of the water spread area, the wet land appears very similar to the water pixels and it becomes very difficult for the eye to decide whether a pixel near the periphery is to be classified as water or land. Moreover, in case of clouds or noise in the scene around the periphery, it is not visually possible to distinguish the water pixels. Using digital techniques, the information of different bands can be utilised to the maximum extent and consistent analysis can be carried out over the entire range of the reservoir. The information about the feature hidden below the clouds can be obtained indirectly using the interpreted imageries of past and future periods. The noise in the imagery can be removed using different algorithms. It is also easy to calculate the water spread area. For these reasons, digital techniques are superior and are gaining recognition now days. For the calculation of water spread area, it is required to find the number of continuous water pixels in the satellite imagery.

Though spectral signatures of water are quite distinct from other land uses like vegetation, built-up area and soil surface, yet identification of water pixels at the water/soil interface is very difficult and depends on the interpretive ability of the analyst. Deep-water bodies have quite distinct and clear representation in the imagery. However, very shallow water can be mistaken for soil while saturated soil can be mistaken for water pixels, especially along the periphery of the reservoir. Secondly, it is also possible that a pixel at the soil/water interface will represent mixed conditions.

In the visible region of the electromagnetic spectrum (0.4 - 0.7 □m), the transmittance of water is quite significant while the absorptance and reflectance are low. The absorptance of water rises rapidly in the near-infrared band while the reflectance and transmittance decrease appreciably. The transmittance of visible radiation through water causes the bottom of the water body to reflect appreciably, transmitted back through the water and detected by the sensor. In such cases, it may not be clear from the visible bands (Band 1, 2 and 3) whether the detected surface is above or below the water surface. For resolving this issue, the image in the near-infrared portion of the spectrum is inspected as a submerged surface will not be detected in this portion of the spectrum. At near-infrared wavelengths, water apparently behaves as a black body absorber and the boundary between the water and other surface features becomes quite prominent. However, along the periphery of the water spread area, the reflectance from the wet land may be quite similar to the reflectance from the adjacent shallow water. For differentiating pixels in such situations, comparative analysis of the digital numbers in different bands needs to be carried out. The signatures of the water and soil/vegetation show opposite trends from the Band 2 (0.53 - 0.59 □m) onwards. Beyond Band 2, with increase in wavelength, water reflectance curve shows downward trend while the soil/vegetation curves show upward trend. This characteristic can be mainly used to differentiate the water pixels from other pixels in all the imageries.

Calculation of Revised Capacity

After finalising the waterspreads of all the images, the histograms are analysed and the water pixels in each image are recorded. Revised area at any elevation is obtained by multiplying the number of water pixels by the size of one pixel. The reservoir elevation at the time of satellite pass is obtained from the reservoir authorities. The reservoir capacity between two consecutive reservoir elevations is computed using the prismoidal formula:

$$V = H (A_1 + A_2 + \sqrt{A_1 * A_2}) /3$$

Where, V is the volume between two consecutive elevations 1 and 2; A_1 is the contour area at elevation 1; A_2 is the contour area at elevation 2 and H is difference between elevation 1 and 2. The revised volume can be compared with the original volume in each zone (obtained from the original elevation-capacity table) and the difference between the two represents the capacity loss due to sedimentation.

3.0 Case Study of Sedimentation Assessment

The results of a few case studies, in which remote sensing data has been used for the computation of sediment deposition in reservoirs, are summarised here.

The state of art of reservoir capacity surveys using remote sensing techniques is only to draw a new level-area-capacity curve and tally the results with the field survey reports. In this study a remote-sensing approach has been attempted for estimation of sedimentation in Bhakra reservoir, located in Satluj basin at the foothills of the Himalayas. Multi date satellite remote sensing data (LISS II sensor of IRS-1B) provided the information on elevation contours in the form of water spread area, which was used, for computing the sedimentation rate. The remote sensing data starting from post monsoon season to next monsoon has been taken from NRSA, Hyderabad. The data were processed and analysed using the ERDAS/IMAGINE 8.3.1 software for determining the water spread area. Each scene of data consisted of 2500 rows, 2520 columns and the information of four bands. While using the temporal satellite data of the same area, it is necessary to geo-reference the images of different time periods. The determination of the water spread area did not require the geo-referencing of the different scenes. But, using the geo-referenced imageries, it was possible to overlay the remote sensing data of different dates. Also using geo-referencing comparison of the change in the water spread area and shrinkage in the water spread with time, particularly the tail end of the reservoir, can be made October image was considered as the master image and about 8 control points were selected for image to image registration. Based on statistics, some points that generated big errors were deleted and replaced by other points to obtain the satisfactory geo-referencing. All the available images were geo referenced following this procedure. After completing this process, different images were displayed one over the other and the superimposition was compared. It was noticed that the geo-referencing was very accurate.

For differentiation of water pixels a generalised algorithm, based on the information of different bands, was adopted. Each pixel has a numerical value called a digital number (DN), that records the intensity of electromagnetic energy measured for the ground resolution cell represented by that pixel. Using the spectral information, the algorithm matches the signatures of the pixel with the standard signatures of water and identifies whether a pixel represents water or not. The spectral signature shows the reflectance/emittance pattern of any object at different wavelengths. The adopted algorithm states " If the DN value of near-IR spectral region, the DN value of water pixels is appreciably less than the DN value of Band 2 and Band 3, then it must be classified as water otherwise not". Since the absorptance of electromagnetic radiation by water is maximum in the near-IR spectral region, the digital number (DN) of water pixels is considerably less than of other land uses. Even if the water depth is very shallow, the increased absorptance in the Band 4 will restrict the DN value to be less than Band 3 and Band 2. If the soil is exposed (may be it is saturated) at the surface, the reflectance will be as per the signatures of the soil which increases with wavelength in this spectral range. Thus, the adopted algorithm clearly differentiates the water pixels from other pixels.

The reservoir capacity between two consecutive reservoir elevations was computed using the trapezoidal formula. In this method, the cross sectional areas of range lines are planimetered and these data, together with surface areas at full reservoir level between adjacent ranges, are used to computed the sediment volumes, as follows:

$$V = \frac{H}{3}(A1 + A2 + \sqrt{(A1 * A2)})$$

Where, V is the volume between two consecutive levels, A_1 is the contour area at elevation 1, A_2 is the contour area at elevation 2 and H is the difference between elevation 1 and 2. The volume of sedimentation deposit between two reservoir levels is computed from the difference between previous capacity survey and satellite derived information.

Water spread area of the reservoir was calculated from satellite data and the level corresponding to the date of pass was collected from the project authority. From the original elevation-area table, the original areas at the intermediate elevations (reservoir elevations on the dates of satellite pass) were obtained by linear interpolation. From the known values of original and estimated areas at different elevations, the corresponding original and revised capacities were determined as mentioned above. The overall reduction in capacity between the lowest and the highest observed water levels was obtained by adding the reduced capacity at all levels.

To estimate the actual silt deposits in the Bhakra reservoir vis-à-vis the project assumptions, hydrographic surveys were carried out in the reservoir annually from 1963 to 1977 and thereafter these surveys were carried out every alternate year. The last hydrographic survey was carried out from October1996 to March 1997. Observing the soundings along predetermined cross sections, approximately 610 m apart, by means of echo sounder carries out the surveys. Superimposing these results on the previous observations for working out the quantity of silt deposited at each cross section and in the whole reservoir, so that they can be relocated every year.

In the present study the cumulative revised capacity of the reservoir at the lowest observed level (450.436 m) was assumed to be the same as the original cumulative capacity (2392.95 Mm^3) at this elevation. Above the lowest observed level, the cumulative capacities between the consecutive levels were added up to arrive at the cumulative original and revised capacities at the maximum observed level. The difference between the original and estimated cumulative capacity represented the loss of capacity due to sedimentation in the live zone of the reservoir. The calculations of sediment deposition for the year 1996-97 are presented in Table 1. In this table volume at different dates have presented which are used to calculate the sediment deposition.

The results show that the volume of sediment deposition from 1965 to 1997, i.e. 32 years between the maximum and minimum observed levels (510.463 m and 450.436 m) works out to be 807.354 Mm^3 (8745.836-7938.482). Assuming a uniform rate of sedimentation, the average rate of sedimentation for this zone is computed to be 25.23 Mm^3 per year.

As mentioned earlier that the capacity surveys have been carried out annually from 1963 to 1977 and thereafter these are carried out on alternate year. The last survey was carried out during 1996-97. The results show that the average annual rate of siltation is about 34.33 Mm^3 for the years from 1965 to 1996 against a designed estimate of 33.61 Mm^3. The result of the sedimentation survey for dead and live loads is given separately. The results of the recent survey taken from this report for the year 1996-97 are given in the Table 2. It can be inferred from the table 2 that the loss in dead storage due to sedimentation is about 668.279 Mm^3, whereas in live storage it is 666.845 Mm^3 in 32 years. Thus according to this survey average sedimentation rate is found 20.88 Mm^3 per year and 20.838 Mm^3 per year for the dead zone and lives zone, respectively. In other words, the sedimentation rate in the both dead and live storage is almost same. For the year 1996-97, the estimated capacity, using remote sensing technique (7938.482 m3) was subtracted from the original capacity (8745.836 Mm^3) at the same level. The loss in capacity (807.354 Mm^3) was attributed to the sediment deposition in the zone of study (510.463 m to 450.436 m) of the reservoir. Thus, the average rate of loss of

Table 1. Assessment of sediment deposition in Bhakra reservoir using remote sensing for the year (1996-97)

Date of satellite pass	Reservoir elevation (m)	Original area (Mm^2)	Revised area using RS data (Mm^2)	Original volume (Mm^3)	Revised volume using RS data (Mm^3)	Original cumulative volume (Mm^3)	Revised cumulative volume using RS data (Mm^3)
15/06/97	450.436	63.538	48.813			2392.950	2392.95
12/1/97	487.734	113.998	99.87	3264.892	2716.47	5657.392	5108.0
21/12/96	494.622	126.572	118.80	828.016	752.157	6485.408	5860.15
7/11/96	506.212	150.406	138.134	1603.107	1487.525	8088.575	7347.675
16/11/96	510.463	158.364	139.688	657.322	590.807	8745.836	7938.482

Table 2. Results of Hydrographic Survey for the Bhakra reservoir (1996-97)

Original designed capacity of reservoir in 1965			Reservoir capacity at the end of 1996-97		
Dead storage (Mm^3)	Live storage (Mm^3)	Total (Mm^3)	Dead storage (Mm^3)	Live storage (Mm^3)	Total (Mm^3)
2431.806	7436.034	9867.84	1763.527	6769.961	8590.571

capacity is computed to be 25.23 Mm^3 per year for live zone using remote sensing data. A comparison of cumulative original and revised capacity obtained using remote sensing technique for the year 1996-97 is shown in Fig. 1. Sedimentation rate in the reservoir obtained using remote sensing approach is slightly higher than obtained from hydrographic survey. The possible reason for this higher sedimentation rate can be attributed to sensitivity in the determination of the water spread area using remote sensing techniques. Moreover mixing of pixels having large proportion of land and smaller proportion of water, around the periphery of the reservoir may also affect the results.

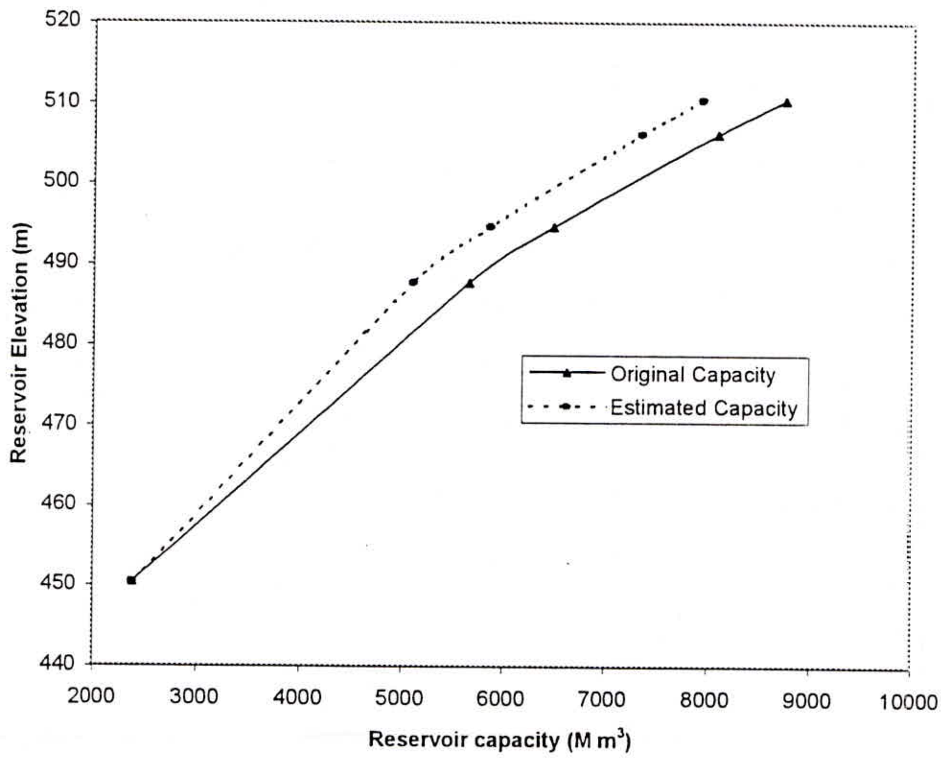

Figure 1: Elevation capacity curves for Bhakra reservoir, India (1996-1997)

4.0 Conclusions and Limitations

Use of Satellite Remote Sensing technique enables a fast and economical estimation of live storage capacity loss due to sedimentation.

- Satellite based method for estimating sedimentation is much easier to adopt since little fieldwork is required. However, because this is a new technology and there can be some errors in interpretation, the accuracy can be doubted. Using this method initially for reservoir where rigorous hydrographic surveys are done will bring out the accuracy and build confidence.

- It would be appropriate if hydrographic surveys are conducted at longer interval and the remote sensing based sedimentation surveys are carried out at shorter interval to make both surveys complementary to each other.
- Capacity estimation by Remote Sensing Technique at regular time interval can give important parameters like annual rate of sedimentation and sediment deposition pattern in the reservoir area and provide new Elevation-Area-Capacity curve for optimal operation of the reservoir.

The basic limitation of the remote sensing based approach is that the revised capacity below the lowest observed level and above the highest observed level can not be determined. It is only possible to calculate the sedimentation rate within the zone of study. From the point of view of operation of reservoir, this limitation is not significant. Since the reservoir rarely goes below the minimum observed level in normal years, the interest mainly lies in knowing the revised capacity and the sediment deposition pattern within the live storage zone. However, if the sedimentation in the entire reservoir is to be found, then the hydrographic survey within the waterspread area corresponding to the lowest observed elevation can be carried out. This will decrease the quantum of efforts in hydrographic survey.