ASSESSMENT OF SEDIMENTATION IN A RESERVOIR USING REMOTE SENSING – SOME CASE STUDIES

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ABSTRACT

Periodic evaluation of sediment deposition and the estimation of available live storage capacity in a reservoir is an integral component of 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 obtained are still not accurate.

Remote sensing data, through its spatial, spectral and temporal attributes, can provide synoptic, repetitive and timely information regarding the revised waterspread area in a reservoir. By using the digital analysis techniques and the geographic information system in conjunction, the temporal change in waterspread area is analysed to evaluate the sediment deposition pattern in a reservoir. In this paper, the remote sensing approach in general, has been described. The approach is explained through some case studies. Inaccuracy in the assessment on account of mis-interpretation of waterspread area, selection of tail end etc. has also been highlighted.

1.0 INTRODUCTION

Soil is eroded due to rainfall and wind, resulting in tremendous sediment movement into watercourses by flood and storm waters. According to an estimate, the global production of sediments is about $15*10^{16}$ tons/year. A great amount of sediment is carried annually by the Indian rivers down to the reservoirs, lakes, estuaries, bays, and oceans. The rivers from Indian sub-continent carry about 6 billion tons of sediments per year. Reservoir sedimentation and consequent loss of storage capacity affects water utilisation. An analysis of sedimentation survey in respect of 43 reservoirs in India indicates that the sedimentation rate varies between 0.3 to 27.85 ha-m/100 sq. km/year (Shangle, 1991). Many of the reservoirs in India are losing capacity at the rate of 0.5 to 1.5 percent annually.

Faced with the high time and space variability of rainfall, more than 3000 river valley projects have already been constructed in India to tap the available water resources for serving various conservation purposes, like water supply for domestic and industrial purposes, irrigation, hydropower generation, navigation and recreation. In view of the limited good storage sites, it is important that live storage of reservoirs be preserved to the extent possible. After the construction & impoundment of a reservoir, there is a great need to continuously monitor the reservoir to:

a) know the quantum of actual annual storage loss in the reservoir due to sedimentation,

b) determine spatial distribution of sediment deposition in the entire body of the reservoir,

c) update the elevation-area-capacity curve for efficient reservoir operation, and

d) undertake remedial measures at the reservoir and watershed level.

For assessing the sediment deposition pattern in a reservoir, systematic capacity surveys are conducted periodically. The most common conventional technique for reservoir capacity evaluation (hydrographic survey) uses direct in-situ measurement of reservoir bed profile. This method requires extensive fieldwork, costly equipment and skilled manpower. Recently, use of hi-tech methods has been started in which hydrographic surveys are carried out employing computerized methods for data collection and analysis. Another conventional technique, the inflow - outflow method involving the measurement of sediments in inflows and outflows, is used only in a very few instances. With the advent of remote sensing technology, it has become very convenient and far less expensive to assess the sedimentation pattern in a reservoir. The spatial, spectral and temporal attributes of satellite data provide synoptic, repetitive and timely information about the revised waterspread conditions which can be used to assess sedimentation pattern in a reservoir.

2.0 REMOTE SENSING BASED SEDIMENTATION ASSESSMENT

After the availability of high resolution indigenous satellite data, capacity surveys of reservoirs by remote sensing technique are gaining much recognition and acceptance. A number of studies using this approach have been carried out [2,3,4,6,7,8,9]. In India, the water level in a reservoir is at higher elevation after the monsoon season (September/October) before it gradually depletes to lower levels towards the end of the drawdown cycle (May/June). Due to the deposition of sediments in the reservoir, the waterspread area at an elevation keeps on decreasing. Using the remote sensing techniques, the revised waterspread area can be determined for different reservoir levels and the revised elevation-capacity curve can be prepared. By comparing the original and the revised elevation-capacity curves, the amount of capacity lost to sedimentation can be assessed. Various steps of the remote sensing based procedure are as follows:

2.1 Selection of Period of Analysis

The availability of good quality satellite data is a factor that should be considered first when selecting the period of analysis. With the launch of IRS-1C/1D satellites, good quality data of these satellites is available and this should not be a limiting factor in most of the studies.

Though this analysis can be carried out for any water year, it is better to select that water year which has maximum variation in the reservoir water level. If the period of analysis is pre-decided, then no further investigation is required on this aspect. Otherwise, a wet year followed by a dry year is the best period of study since such a sequence will largely cover the entire operable range of the reservoir. The information about maximum and minimum water levels in different years can be gathered from the dam authorities and the year of analysis can be decided.

The amount of sediment deposition in the delta region of a reservoir largely depends on the characteristics of sediment load in the stream and the time elapsed since the first impoundment of the reservoir. Since the remote sensing based analysis involves the change detection in the waterspread area and the size of one pixel is quite large (36 m for LISS-II and 24 m for LISS-III), it is necessary to ensure that detectable change in the waterspread conditions has occurred in the reservoir. For this reason, it may not be worthwhile to carry out such analysis for each year or every alternate year. In general, sedimentation assessment using remote sensing must be made for major reservoirs after a gap of about 5 years or after a major flood event.

2.2 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)] – 1988 onwards

b) IRS - 1C/ IRS – 1D [PAN (5.8 m) & LISS-III (23.5 m)] – 1996 onwards

c) LANDSAT [MSS (80 m) & TM (30 m)]

d) SPOT [PAN (10 m) & spectral (20 m)]

Multi-spectral information is required to identify and differentiate the water pixels from the peripheral wet land pixels. It is also desirable to use the data of higher resolution for obtaining accurate results. At present, the remote sensing data of indigenous IRS satellites can be used and is a better choice from the cost and resolution considerations.

2.3 Processing of Remote Sensing Data

The basic output from the remote sensing analysis is the waterspread area on the date of satellite pass. Two techniques of remote sensing interpretation, i.e. visual and digital, are used for waterspread delineation. Visual techniques are based purely on the interpretative capability of the analyst and it is not possible to use the information of different bands after the generation of visual product. Around the periphery of the waterspread area, the wet land pixels appear 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. Using digital techniques, the information of different bands can be utilised to the maximum extent. The visual techniques are rarely used now. The steps of digital processing are as follows:

Geo-Referencing

The multi-temporal remote sensing images are first geo-referenced to a master map, say a SOI toposheet or the original drainage map of the area. Using the geo-referenced images, the waterspread areas at different time periods can be compared. Geo-referenced images are also helpful in manipulating the information at the locations of cloud and noise pixels from the images of adjacent dates. Revised contours can be prepared and overlaid.

Identification of Water Pixels

This is the basic output of the remote sensing interpretation and the most important component of the analysis. In the visible region of the spectrum (0.4 - 0.7 μm), the transmittance of water is significant and the absorptance and reflectance are low. The absorptance of water rises rapidly in the near-IR where both, the reflectance and transmittance are low. At near-IR wavelengths, water apparently acts as a black body absorber. Though the spectral signatures of water are quite distinct from other land uses like vegetation, built-up area and soil surface, yet the identification of water pixels at the water/soil interface is very difficult and depends on the interpretative ability of the analyst. Deep-water bodies have quite distinct and clear representation as compared to shallow water. Shallow water can be mistaken for soil while saturated soil can be mistaken for water, especially along the periphery of reservoir. To differentiate water pixels from the adjacent wet land pixels, comparative analysis of the digital numbers in different bands is usually carried out. The methodologies, in general, can be classified in three categories:

Classification - In this method, the image is classified using supervised or unsupervised classification by identifying training sets of different classes.

Thresholding - In this method, a threshold value is adopted in the near-IR image to separate out the water body from surrounding soil/vegetation. This is the most commonly used method.

Modeling - In this method, a model that tests multiple conditions, is applied to determine whether a pixel represents water or not. This methodology may involve integrating multi-band thresholding, or defining relation between different bands. Many current applications seek to refine the models for better demarcation.

The resulting images of water pixels are compared with the near-infrared (NIR) image and the standard false colour composite (FCC). After the identification of water, the extended channels and discontinuous pixels need to be edited. If original data contains the noise and cloud pixels, then interpretation at such locations is made from the subsequent date imageries.

Removal of Discontinuous Pixels

The contour area represents only the continuous waterspread area at any elevation. Due to the presence of local depressions within the islands in the reservoir and around the periphery of the reservoir, a few pixels in these depressions appear as water pixels. These pixels do not form part of the continuous waterspread and need to be removed. The water image is edited manually to remove these discontinuous pixels.

Removal of Extended Tail and Channels

In addition to the main river at the tail end, numerous small channels usually join the reservoir from different directions. The elevation of water in these channels and main river remains at higher than that of reservoir water surface. So, the extended tail and channels must be removed from the point of termination of spread. The selection of truncation point is subjective and can be based on the difference between the water levels in the subsequent date imageries. The water pixels beyond the truncation point are removed by manual editing. Similarly, the water pixels in the river downstream of the dam are not part of reservoir waterspread and need to be removed.

Interpretation of Noise and Cloud Pixels

If an image contains noise and cloud pixels, then water image of subsequent dates will have to be used to ascertain the properties at corresponding locations. The interpretation is based on the reasoning that the waterspread area at the lower elevation must always be contained within the waterspread at higher elevation. This logic does not hold good if such pixels are located at the periphery of the waterspread.

Derivation of Revised Contours

After finalising the waterspread area for a particular image, the periphery of the waterspread area can be derived using the image processing techniques. Three different kinds of filters, namely Edge Detection, Horizontal and Vertical can be used and their results can be integrated to obtain the peripheral pixels of a waterspread area. The elevation value can be assigned to each contour and different contours can be overlaid to represent the revised conditions within the zone of study. If the original contours of the area are available, then the original and revised digital elevation models (DEM) can be prepared. The difference between the two gives the spatial distribution of depth of sedimentation. However, this exercise requires perfect registration of the original and revised contours.

2.4 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:

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

where, V is the volume between two consecutive elevations 1 and 2; A_1 and A_2 are contour areas at elevation 1 and 2 and ΔH is the 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 POSSIBLE SOURCES OF ERROR

Though the technique appears to be simple and straight forward, the results can deviate from the true value because of some error in the interpretation of water pixels and in the selection of tail end. These factors are briefly discussed in the following:

3.1 Mis-Interpretation of Water

Among various sources of errors, this is the most important factor that can cause appreciable error in the results. The main objective of remote sensing based approach is to clearly identify the water pixels and differentiate them from the peripheral wet land. It is very difficult to define a true threshold in near-IR band for water pixels because the reflectance properties of water change due to the presence of suspended sediment particles, atmospheric effects, bio-mass etc. Even if multi-spectral data are used by way of ratioing of bands or calculating NDVI, a differentiation limit needs to be defined. There is no generalised algorithm to identify water pixels exclusively. This way, some pixels can be mis-interpreted as water or land. A small error in the areal estimation of waterspread can have significant effect on the calculation of sediment volume.

As the spatial resolution of satellite data is improving, the error due to mis-interpretation is expected to reduce. Further research is needed on this aspect and it is important to develop a generalised and objective algorithm before the remote sensing approach can gain wider acceptance.

3.2 Selection of Tail End

From the remote sensing image, it is not possible to identify the true point of truncation of the tail end. Based on one's personal judgement, it can be taken as the point where the reservoir spread is terminating. In a number of past studies, a mask of waterspread corresponding to FRL has been generated and the tail end in subsequent date images is considered up to the mask. However, this does not have universal acceptance. This is the limitation of the conventional methods also.

3.3 Error in Original Elevation-Capacity Curve

Since the sedimentation volume is computed by subtracting the revised capacity between two elevations from the original one, the accuracy of original elevation-capacity curve directly affects the results of this analysis. This is also the limitation of the conventional methods.

4.0 CASE STUDIES OF SEDIMENTATION ASSESSMENT

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

4.1 Dharoi Reservoir

The Dharoi dam, located on the river Sabarmati in the Gujarat state, was constructed in the year 1976. In this study, the volume of sediments deposited in the Dharoi reservoir was quantified using remote sensing data and the spatial distribution of suspended sediments in the reservoir was analysed in different time periods of a water year. Digital image analysis was carried out using the ERDAS 7.5 image processing system.

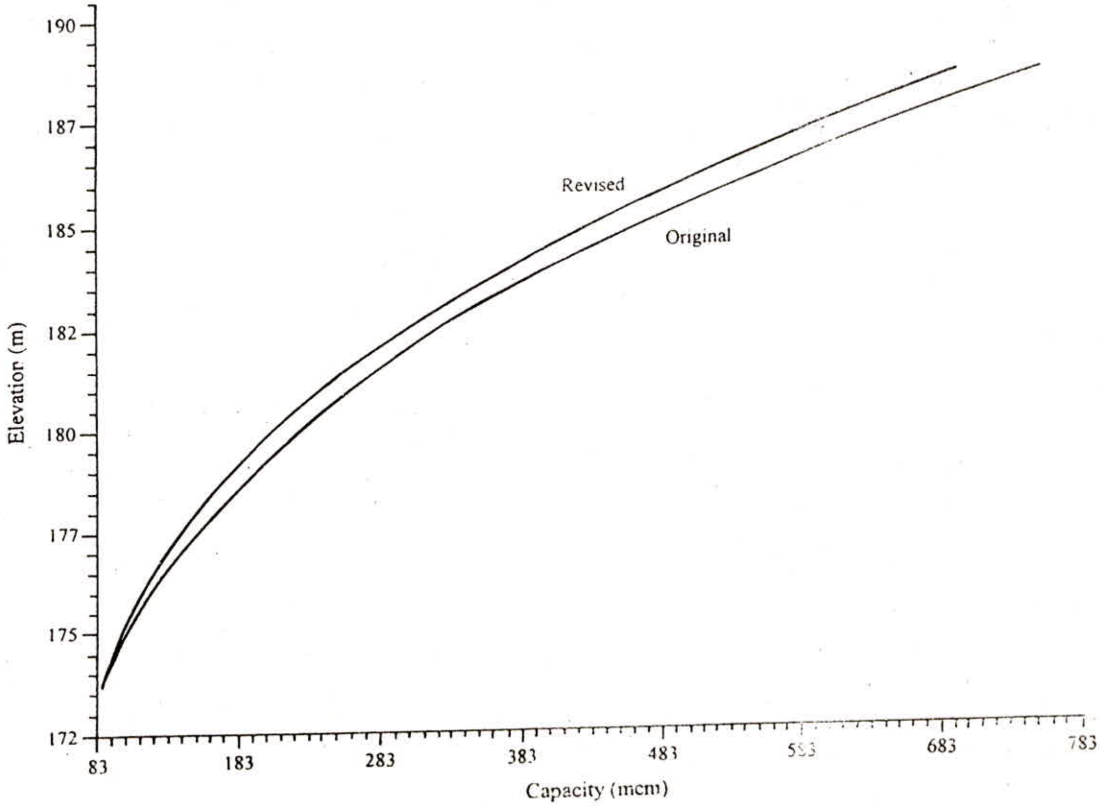

Fig. 1 : Original & Revised Elevation-Capacity for Dharoi Reservoir

Multi-temporal data of IRS-1A satellite and LISS-II sensor were used for the period Oct., 1989 to April, 1990. Since the year 1987 was a drought year, data of May, 1988 was also used. During the period of study, the water level varied from 187.98 m (FRL 189.59 m) to 172.96 m (MDDL 175.76 m). Thresholding of NIR band was carried out to separate the water pixels in all the eight images. The discontinuous water pixels were removed by editing and the waterspread area was calculated. It was found that approx. 57.27 million cubic meter (MCum) of sediments had deposited in the zone of study in the span of 14 years. The original and revised elevation-capacity curves are presented in Fig. – 1.

4.2 Ukai Reservoir

Ukai is the largest multipurpose project so far completed in Gujarat state. The dam is located across river Tapi in district Surat in Gujarat state. The total catchment area of the Ukai reservoir is 62,225 sq. km. The dam was completed in the year 1972. For this study, multi-temporal data of IRS-1B satellite and LISS-II sensor were used for the period Nov., 1993 to June, 1994. During the period of study, the water level varied from 104.45 m (FRL 105.15 m) to 92.20 m (MDDL 82.30 m). The reservoir waterspread was covered in A1 quadrant of Path 30 and Row 53 of the satellite.

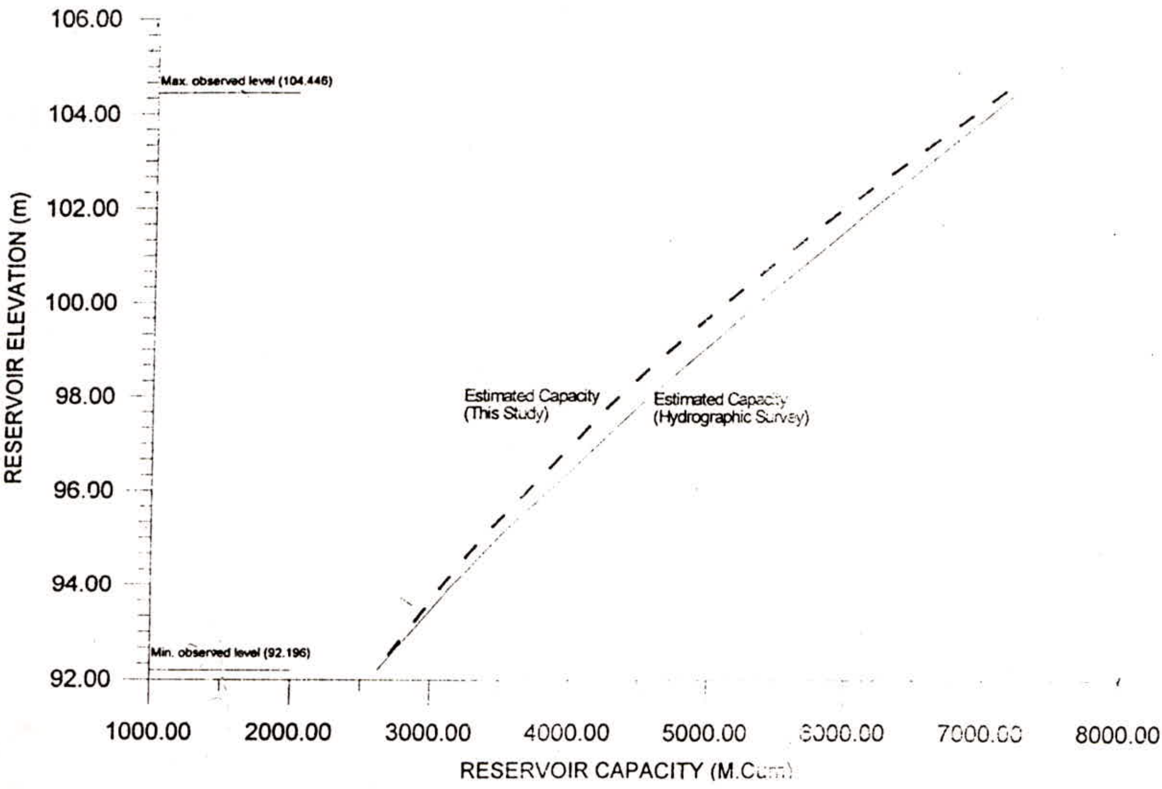

Fig. 2 : Comparison of Results of Remote Sensing with Hydrographic Survey for Ukai

The data were processed and analysed using the ERDAS/IMAGINE 8.3.1 software. Temporal satellite images were geo-referenced. A generalised algorithm (digital number in NIR band less than red band and green band) was used for differentiating the water pixels in all the images. The resulting water images were compared with the NIR band and the FCC and the interpretation was satisfactory in all the cases. A few images were having noise and cloud problems and the same were sorted out using the subsequent date images. The tail end of the reservoir was truncated on the basis of termination of water spread conditions. The results indicate a loss of 340.4 MCum of storage capacity in the zone of study in a period of 21 years. Thus the rate of sedimentation comes out to be approx. 16.2 MCum/year. The hydrographic survey of the reservoir was conducted in the year 1992. The results of remote sensing survey and the hydrographic survey are presented in Fig. – 2.

4.3 Bargi Reservoir

Bargi is one of the major reservoirs on the Narmada river in M.P. This reservoir was first impounded in the year 1989. The post-monsoon period of the year 1996-97 was chosen for analysis. The remote sensing data of IRS-1C satellite and LISS-III sensor were acquired for nine different dates and the revised water spread areas were extracted. Using the trapezoidal formula, the revised capacity in between the maximum level of 421.45 m (FRL 422.76 m) and the minimum level of 406.00 m (MDDL 403.55 m) was obtained. The generalised algorithm applied in the Ukai analysis did not work in all the images in this case. Hence, a threshold limit on normalised difference water index ((NIR-RED)/(NIR+RED)) image was applied after comparing the results with the FCC and the NIR band data. The tail end was obvious in most of the images.

The results of this study demonstrate that the available capacity in the zone of study has reduced by 26.67 M Cum from the original capacity (2585.56 M Cum). As per the CWC report of Bargi project sedimentation, the total sedimentation in the entire reservoir for this period was estimated at 85.74 M Cum. The height of the zone of study is about one third of the height of the dam from bed level to the FRL. This reservoir has significant tail portion as compared to its main body. A plot of the contour derived using remote sensing (419.55 m) is made with the original contour (420.00 m). The comparison of the two shows that the contour derived from remote sensing approach matches quite closely with the original contour.

5.0 ADVANTAGES & LIMITATIONS OF REMOTE SENSING APPROACH

The conventional methods, such as hydrographic surveys, are laborious, costly and time consuming. The hydrographic surveys of reservoirs are being conducted at a frequency of 2 to 15 years, though the recommended frequency is 5 years. Remote sensing technique has emerged and established itself as a useful, cost and time effective tool to estimate capacity loss.

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 fluctuation of water level. From the point of view of operation of reservoir, this limitation is not significant. Since the reservoir rarely goes below

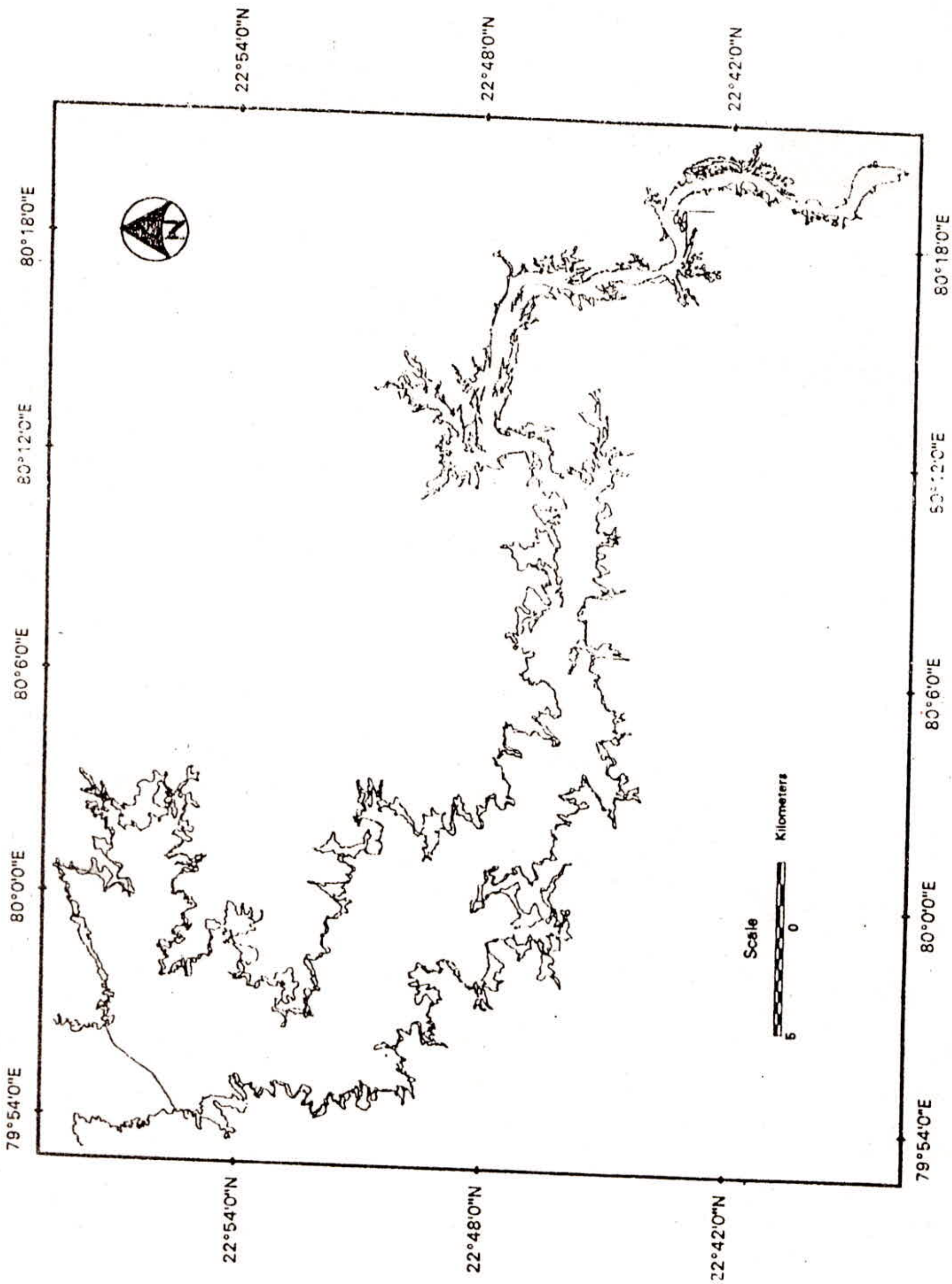

Fig. 3 : Vomparison of Derived Contor (419.55m) with Original Contour (420.00m)

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. It is seen that the estimation of sedimentation by remote sensing is highly sensitive to: (a) the accuracy in determining the waterspread area, (b) the accuracy of water level information, and (c) the accuracy of the original elevation-area-capacity table.

6.0 CONCLUDING REMARKS

The conventional techniques of sediment quantification, like the hydrographic survey and inflow-outflow methods, are cumbersome and time consuming. With the introduction of remote sensing techniques, it has become very cost-effective and convenient to estimate the sediment deposition in the various zones of a reservoir. If the original contours of submergence at closer elevation interval are available, then the spatial depth of sedimentation can also be determined.

At present, water pixels are identified using various digital processing techniques, like density slicing, classification or modelling of multi-spectral data. These methods need subjective interpretation. Accuracy in the identification of water pixels and selection of tail end affect the accuracy of sedimentation assessment using remote sensing. There is an urgent need to develop a generalised algorithm for the identification of water pixels.

The satellites of higher spatial resolution are now becoming available and the same must be utilised to increase the accuracy of the waterspread determination. Remote sensing images can be chosen at closer time intervals so that maximum number of elevations within the zone of variation can be covered.

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