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# Assessment of sediment deposition pattern in Bargi reservoir using digital image processing

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## Abstract

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

Due to sedimentation, the water-spread area of reservoir at various elevations keeps on decreasing. Remote sensing technique, through its spatial, spectral and temporal attributes, provides synoptic and repetitive information on water-spread area of a reservoir. By use of remote sensing data and a geographic information system in conjunction, the temporal change in water-spread area can be analysed to evaluate the sediment deposition pattern in a reservoir. A case study, related to the assessment of sediment deposition in Bargi reservoir, M.P. State, India, is presented. The reservoir was completed in the year 1988 and no hydrographic survey has yet been carried out. Under these circumstances, the sedimentation assessment using satellite data can guide the dam operators in updating the elevation-area- capacity table of the reservoir. The images of nine dates of IRS-1C satellite, LISS-III sensor have been analysed using the ERDAS/IMAGINE software. The sedimentation rate in the zone of study comes out to be about 0.023 ha-m/sq. km/year.

## 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. Soil erosion in India is taking place at the rate of approximately 16 ton/ha/year out of which about 10 % is deposited in reservoirs and 29% is transported to sea (Narayan et al, 1983). Reservoir sedimentation and consequent loss of storage affects water availability and operation schedule. 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. Due to continuous encroachment of the live storage by the sediments, this topic is gaining much attention now-a-days (Garde, 1995; Varshney, 1997; Morris et al, 1997).

Faced with the high time and space variability of rainfall, more than 3000 major and medium river valley projects have been constructed in India to tap the available water resources to serve various conservation purposes and to control flooding. In view of availability of limited good storage sites because of topographical constraints, it is important that live storage capacity of existing 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 conservation measures at the reservoir and watershed level.

To assess the sediment deposition pattern in a reservoir, systematic capacity surveys are conducted periodically. The practice of sedimentation survey of reservoirs in India dates back to 1870. However, systematic surveys started only in 1958 when the Central Board of Irrigation and Power undertook a major scheme of reservoir sedimentation survey and 28 major reservoirs were surveyed (CBIP, 1981). The most common conventional technique (hydrographic survey) use direct in-situ measurement of reservoir bed profile. A hydrographic survey requires extensive fieldwork, costly equipment and skilled manpower. In India, hydrographic survey using echo-sounder along range lines has mostly been adopted. Recently, use of hi-tech methods of hydrographic survey employing satellite based global positioning systems and computerized methods for data collection and analysis has started. The data received from echo-sounder is automatically logged in the computer, edited and the volume of sedimentation can be calculated. Another technique, the inflow - outflow method, involving measurement of sediments in inflow and outflow is used only in very few instances. The mathematical models that have been developed for this purpose include HEC-6, GSTARS, FLUVIAL, TABS etc (Morris et al, 1997).

With the advent of remote sensing technology, it has become very convenient and far less expensive to assess the sedimentation pattern in a reservoir. In this study, the results of a case study of Bargi reservoir in the Narmada basin, M.P. State, India are presented and the advantages and limitations of the remote sensing approach are discussed.

## REMOTE SENSING BASED APPROACH

With the availability of high resolution 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 [1,2,4,5,6,7,11]. In India, the water level in a reservoir is near the FRL by the end of the monsoon season (September/October) before it gradually depletes to lower levels towards the end of the drawdown cycle (May/June). Due to deposition of sediments in the reservoir, the water-spread area at an elevation keeps on decreasing. Using the remote sensing approach, the water-spread area is determined at different reservoir levels and the revised elevation-capacity curve is prepared. By comparing the original and revised elevation-capacity curves, amount of capacity lost to sedimentation can be assessed.

Clearly, the analysis for the water year which has maximum variation in the reservoir water level will be most useful. The satellite imagery is analyzed using either visual or digital processing techniques and the water-spread area is delineated. Knowing the waterspread area for a particular image, the periphery of waterspread area is derived using various image processing filtering techniques. Elevation values are assigned to each and contours corresponding to different waterspreads are overlaid to represent the revised conditions in the various zones. The reservoir capacity between two consecutive elevations is computed using the prismoidal formula. This way, the revised elevation-capacity table is generated. A comparison of this table with the original elevation-capacity table gives the capacity loss due to sedimentation in various zones of the reservoir.

## DESCRIPTION OF THE BARGI RESERVOIR

The Narmada river rises in the Mikel range in Shahdol district, M.P. state, India, near Amarkantak at an elevation of 1050 m. The river flows through the city of Jabalpur and enters the fertile Narmada valley, which is a long and narrow strip, walled by Vindhyas on the north and Satpuras on the south.  This river finally discharges into the Gulf of Khambat. In the series of major dams to be constructed on the river Narmada in Madhya Pradesh, the Bargi project is one of the major schemes, which have been completed till date.

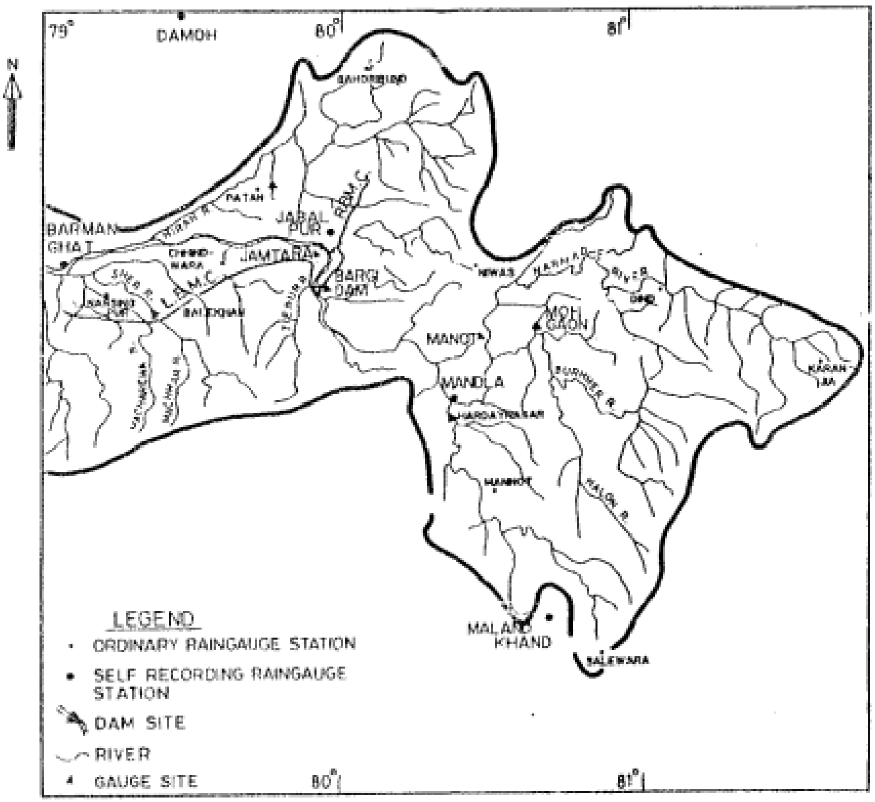

**Figure 1. Index map of Narmada basin up to Bargi dam.**

Bargi is a composite earth and masonry dam, 5374.39 m long constructed near village Bargi in the Jabalpur district. The project has been envisaged as a multipurpose scheme meant to serve for water supply for domestic and industrial purposes, irrigation and hydropower generation. The dam is located 43 km downstream of the Jabalpur city. The latitude and longitude of the dam are 22°56′30″ N and 79°55′30″ E respectively. The index map of the basin is presented in Figure – 1. The catchment area at the dam site is 14556 sq. km. The Bargi reservoir (now known as Rani Avanti Bai Sagar), has the maximum reservoir level, full reservoir level and the dead storage level at 425.70 m, 422.76 m and 403.55 m respectively. The gross, live, and dead storage capacities of the reservoir are 3.92 billion cubic meters (B Cum), 3.18 B Cum and 0.740 B Cum respectively. The maximum height of the masonry dam is 69.80 m while that of earth dam is 29 m. The reservoir has been classified as hilly according to the I.S. code no. 5477. The shape of the reservoir is almost longitudinal. Its longest periphery from the axis is about 80 km.

The average annual rainfall in the catchment up to Jamtara is 1414 mm. About 94% of the annual total rainfall occur during the monsoon season (July to October). The average annual inflow at the dam site is 7197 million cubic meters (M Cum). The dam was first impounded up to RL 407.5 m in the year 1988. In subsequent years 1989 and 1990, the reservoir was filled up to RL 418.5 m, 422.76 m respectively. No hydrographic survey has yet been carried out for the reservoir.

## DATA AVAILABILITY

For the Bargi reservoir, the historical record of annual maximum and minimum observed levels was obtained from the dam authorities. Maximum variation in water level (406.00 m to 421.45 m) was observed in the year 1996-97, covering most of the live storage zone (403.55 m to 422.76 m). Therefore, the period from October, 1996 to June, 1997 was selected for analysis.

The multispectral data of IRS-1C satellite, LISS – III sensor were available for the period of analysis and were used in this study. Bargi reservoir water-spread was covered in one scene of Path 100 and Row 56 of satellite. Based on the status and availability of remote sensing data and the time spacing in-between the satellite data, nine scenes were obtained for the following dates of pass: 10.10.96, 03.11.96, 27.11.96, 07.02.97, 03.03.97, 27.03.97, 20.04.97, 14.05.97, and 07.06.97. The water levels on these days were obtained from the dam authorities.

## INTERPRETATION AND ANALYSIS

The basic output from the remote sensing analysis is the waterspread area on the date of satellite pass. Two techniques of remote sensing interpretation, viz., 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 to visually judge 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. In this study, digital processing was carried out using the ERDAS/IMAGINE image processing software. The steps of analysis are described in the following.

## Import, Visualisation and Geo-referencing

The data of IRS-1C satellite and LISS-III sensor for nine different dates were received from NRSA on CD-ROM media and the same were imported in the ERDAS system. The pixel size of the processed data was 24 m. A false colour composite (FCC) of Near-Infra red (NIR), Red and Green bands combination was prepared. The water-spread area (except at the periphery) of the reservoir was quite distinct and clear in the FCC. Reservoir water-spread area was free from clouds and noise in all the nine imageries.

The multi-temporal remote sensing images are first geo-referenced to a master map. Using the geo-referenced images, the waterspread areas at different time periods can be compared and revised contours can be overlaid. First, the drainage pattern of the area around and within the reservoir waterspread was digitised from 1:50,000 scale toposheets of the Survey of India (SOI). The toposheets of higher scale were not available. The drainage pattern was rasterised and resampled in Polyconic projection to a pixel size of 24 m (same as remote sensing data). In the similar way, the original contours of the catchment upstream of the dam site were digitised. The contours on these toposheets were available for elevations of 400 m, 420 m, 440 m and 460 m.

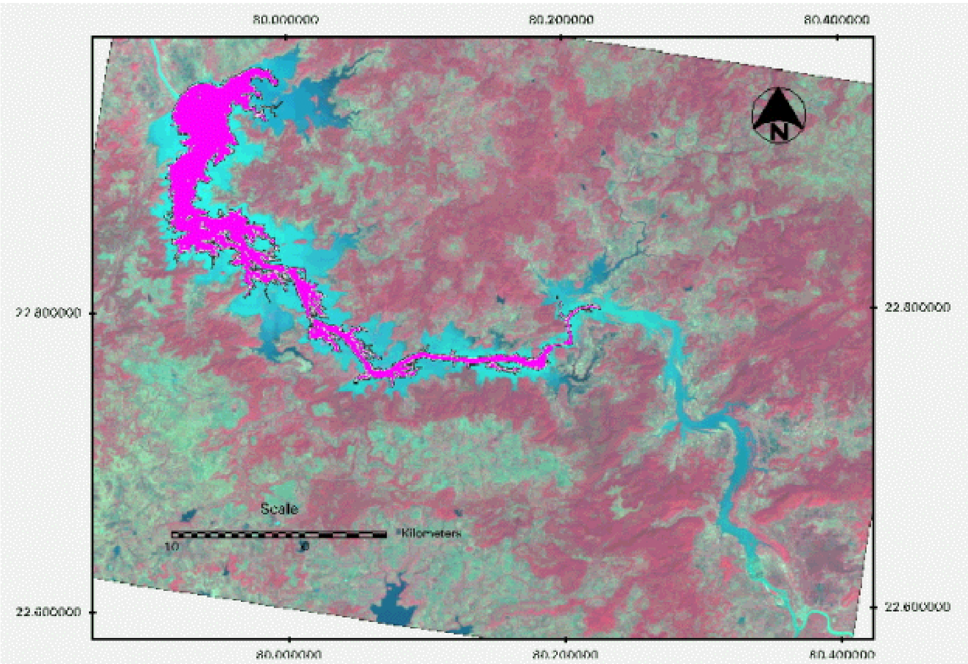

**Figure 2. Image of Bargi reservoir on October 10, 1996 overlaid with water-spread of June 7, 1997.**

Next, image–to–image registration was carried out for all the images. Each imagery was georeferenced with its subsequent date image. The results were checked for all the images by displaying two images at a time one over the other and comparing the two using the SWIPE facility. The match between the images was satisfactory. After image–to-image registration, the resulting images were georeferenced with the drainage map. All the images were georeferenced with the drainage map using the similar model, since all of them were already georeferenced with each other. The FCC of georeferenced image of Bargi reservoir of 10 October, 1996 is shown in Figure – 2. The water-spread image of June 07, 1997 is overlaid on this image to have a view about the overall waterspread variation in this analysis.

## IDENTIFICATION OF WATER PIXELS

This is the basic output of the remote sensing interpretation and is the most important part of 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, 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 was carried out. The methodologies, commonly used in digital processing are classification, thresholding and modeling.

After analysing the spectral reflectance of water pixels in various imageries, an algorithm was used to identify water pixels using data of different bands. The algorithm matches the signatures of a pixel with that of water and then identifies whether a pixel represents water or not. In addition, it also checks for the *Normalised Difference Water Index* ((Green-NIR)/(Green+NIR)) which is created as a separate image. In all the images, it is found that the NDWI for water is either equal to or greater than 0.44. The algorithm checks for following condition for each pixel. If the condition is satisfied, then the pixel is recorded as water, otherwise not:

*"If the DN value of NIR band of a pixel is less than the DN value of the Red band and the Green band, and the NDWI is ≥ 0.44, then it is classified as water otherwise not".*

Since the absorptance of electromagnetic radiation by water is at maximum in the NIR spectral region, the DN value of water pixels is appreciably less than those of other land uses. Even if the water depth is very shallow, the increased absorptance in the NIR cause the DN value to be less than Red and Green band. This condition differentiates the water pixels from other pixels. The condition was applied in the form of a model in the ERDAS/IMAGINE software and the model runs were taken with images of different dates. The resulting images of water pixels were compared with the near-IR images and the standard FCC. The results were found to be satisfactory in all the cases. The biggest advantage of this method was that it avoided the necessity of selecting different limits in different images as required in density slicing.

## Removal of Discontinuous Pixels

The main objective of calculating the water-spread area is to determine the revised contour area at the elevation of the water surface. Since the contour area represents the continuous area, it is required that the isolated water pixels surrounding the waterspread area and/or located within the islands be removed from the interpreted water image. Similarly, the water pixels downstream of the dam do not form part of reservoir and need to be removed.

To remove most of these unwanted pixels, a mask was generated from the edited water image of October 10, 1996. The water image of this date was manually edited to remove the discontinuous pixels and the downstream river pixels. Next, the water images corresponding to remote sensing images of all dates were obtained by applying the model as mentioned above. The mask was superimposed and all the pixels outside the mask were treated as if they are not part of the reservoir. Most of the discontinuous pixels could be removed in this step. However, some of the pixels, that were discontinuous and lie within the mask, still needed to be edited. To remove these pixels, a GIS utility known as “CLUMP” was used. An 8-connected clump image was formed for all the water images. This utility created a clump around the discontinuous pixels and assigned different values to different clumps. Using the “MODELER” option, these clumped pixels were removed so that only continuous water-spread remained in the water image.

## Removal of Extended Tail and Channels

The main river at the tail end of the reservoir and numerous small channels join the reservoir from different directions around its periphery. Water in these channels is classified as water. However, the elevation of water in these channels and the main river remain higher than the water surface of the reservoir. So, the extended tail and channels must be removed from the point of termination of spread. The selection of truncation point is subjective and may be based on the difference between the water levels in the subsequent date imageries.

In the present case, there were no extended channels around the periphery of the reservoir. Further, there was no need to identify the tail end in eight out of nine imageries except for the image of October, 1996. In eight imageries, the termination of water spread was obvious.

## Derivation of Revised Contours

After finalising the waterspread area for a particular image, the periphery of the waterspread area was derived using various digital processing techniques. First, the islands within the spread area and the diagonally connected pixels were removed. This was achieved using the CLUMP, in the same way, as was done for removing the discontinuous water pixels. Then, three different kinds of filters, namely Edge Detection, Horizontal and Vertical were convoluted with the total waterspread image. After obtaining the final peripheral pixels, the elevation values were assigned to them using the MODELER. The revised contours of the reservoir water-spread, as obtained from remote sensing analysis are presented in Figure – 3.

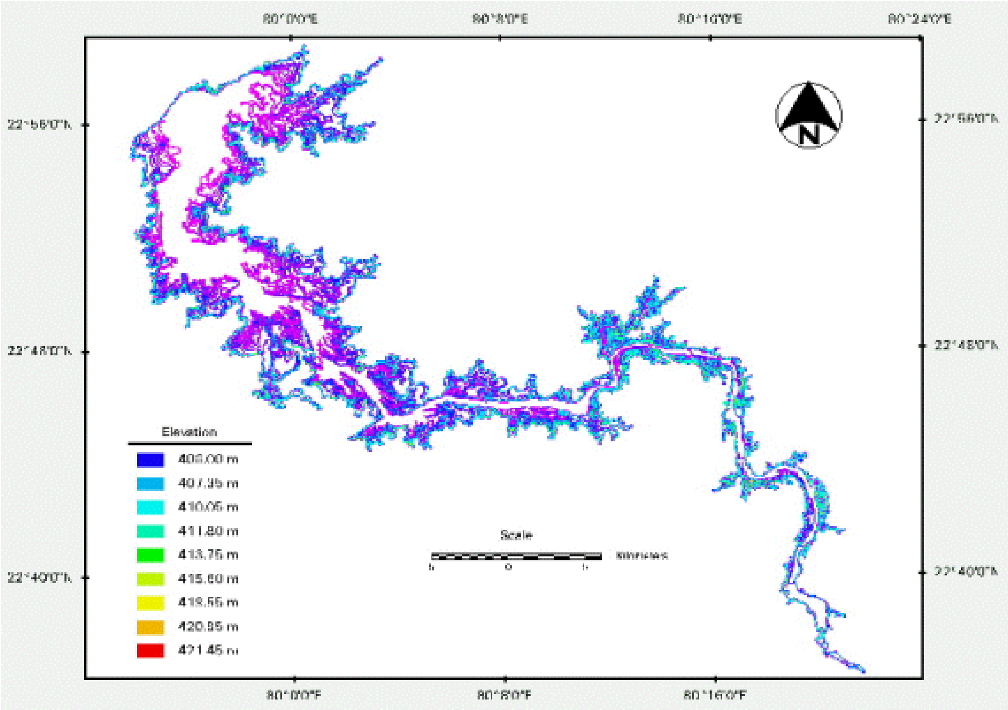


**Figure 3. Revised contours of Bargi reservoir.**

## Calculation of Revised Capacity

After finalising the waterspreads of all the images, the histograms were analysed and the water pixels in each image were recorded. Water spread area at any elevation was obtained by multiplying the number of water pixels by the size of one pixel (24m x 24m). Reservoir capacity between two consecutive reservoir elevations was computed using the prismoidal formula:

$$V = \Delta H \left(A_1 + A_2 + \sqrt{A_1 * A_2}\right) / 3 \qquad (1)$$

where, V is the volume between two consecutive elevations 1 and 2; $A_1$ and $A_2$ are contour areas and $\Delta H$ is the difference between elevation 1 and 2. The original elevation-capacity table before the impoundment of dam (1988) was obtained from the Reservoir Operation & Maintenance manual of the Narmada Valley Development Department, Govt. of Madhya Pradesh. From the original elevation-capacity table, the original capacity at the intermediate elevations (reservoir elevations on the dates of satellite pass) was

obtained by linear interpolation. The revised volume was compared with the original volume in each zone and the difference between the two is the capacity loss due to sedimentation.
The cumulative revised capacity of the reservoir at the lowest observed level (406.00 m) was assumed to be the same as the original cumulative capacity (1010.00 M Cum) at this elevation. Above this level, the cumulative capacities between the consecutive levels were added up so as to arrive at the cumulative revised capacity at the maximum observed level (421.45 m). The calculation is presented in Table - 1.

**Table 1. Calculation of Sediment Deposition in Bargi Reservoir Using Remote Sensing.**

| Date of Satellite Pass | Reservoir Elevation (m) | Revised Area (R.S.) ($Mm^2$) | Original Volume ($Mm^3$) | Revised Volume (R.S.) ($Mm^3$) | Original Cumulative Volume ($Mm^3$) | Revised Cumulative Vol. (R.S.) ($Mm^3$) |
|---|---|---|---|---|---|---|
| 10.10.96 | 421.45 | 256.190 | 139.966 | 126.65 | 3595.833 | 3568.89 |
| 03.11.96 | 420.95 | 250.430 | | | 3455.867 | 3442.24 |
| | | | 391.904 | 341.64 | | |
| 27.11.96 | 419.55 | 237.680 | | | 3063.963 | 3100.60 |
| | | | 860.072 | 837.84 | | |
| 07.02.97 | 415.60 | 187.530 | | | 2203.891 | 2262.76 |
| | | | 306.907 | 325.72 | | |
| 03.03.97 | 413.75 | 164.842 | | | 1896.984 | 1937.04 |
| | | | 262.161 | 297.29 | | |
| 27.03.97 | 411.80 | 140.405 | | | 1634.823 | 1639.75 |
| | | | 213.942 | 227.24 | | |
| 20.04.97 | 410.05 | 119.580 | | | 1420.881 | 1412.51 |
| | | | 290.028 | 286.39 | | |
| 14.05.97 | 407.35 | 093.112 | | | 1130.853 | 1126.12 |
| | | | 120.853 | 116.12 | | |
| 07.06.97 | 406.00 | 079.106 | | | 1010.000 | 1010.000 |
| | | | 1010.00 | 1010.000 | | |

## DISCUSSION OF RESULTS

The results show that the revised capacity in the zone under consideration (between RL 406.00 m and 421.45m) is 2558.89 M Cum while the original capacity as calculated and envisaged in the project before the impoundment of the dam was 2585.56 M Cum. Thus, it can be inferred that 26.67 M Cum of the capacity has been lost to sedimentation in the zone under study in a period of 8 years (1989 to 1996). The year 1988 was not considered because the impoundment of dam in that year was only up to 407 m. Thus, the rate of sedimentation in the reservoir comes out to be 3.33 M Cum per year.

The results of this study were compared with the sedimentation study report prepared by Central Water Commission. In this study, the trap efficiency of 95% was assumed. Based on the upstream developments, the report predicted that the total sediment trapped in the reservoir will be 5746.5 ha-m during the period 1989 to 1993 and 5655.0 ha-m during the period 1994 to 1999. Thus, the total sediment that will get trapped in the whole of the reservoir (367 m to 422.76 m) during the period from 1989 to 1996 will be 8574 ha-m. The results of the present study show that 2667 ha-m of sediment has deposited in the zone from 406.00 m to 421.45 m. The height of dead storage zone of this reservoir (367.00 m to 403.55 m) is about 36.5 m while that of live storage zone (403.55 m to 422.76 m) is 19.21 m. The tail portion of the Bargi reservoir is quite significant as compared to the main body of the reservoir. Since the reduction in velocity in the tail portion of this reservoir is only marginal, the sediment carrying capacity does not reduce appreciably resulting in the transportation of most of the sediments towards the main reservoir and their deposition at greater depths.

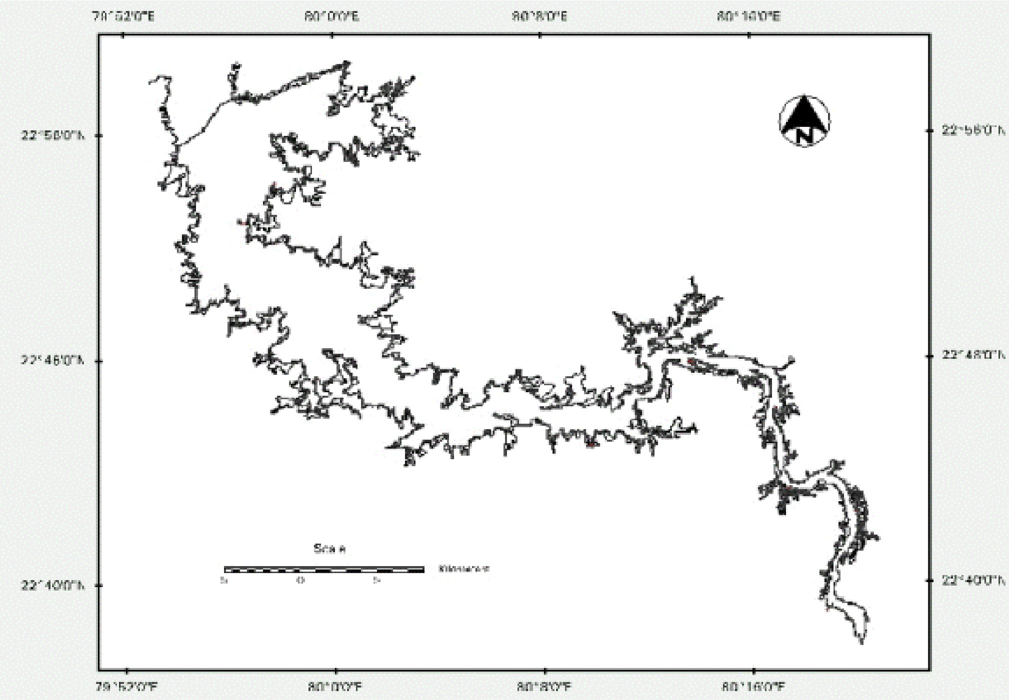

**Figure 4. Comparison of original contour (420.00 m) with derived contour (419.55 m).**

It is important to note that the accuracy of assessment of sedimentation depends on the accuracy of the original capacity table. The Bargi reservoir has a dendritic shape with a number of narrow but long branches jutting out at many places, in addition to the main tail. It is possible that at the time of project survey, many of these tails were not considered in the calculation of original capacity. To check this aspect, a comparison was made between the original and revised contours. The original contour of 420 m and the revised contour of 419.55 m elevation are plotted in Figure – 4. At few places, it is observed that the original contour is lying inside of the revised contour which should not happen in normal circumstances unless significant erosion has occurred at those places. The comparison further shows that at other places, the contour derived from remote sensing matches quite closely with the original contour.

## ADVANTAGES & LIMITATIONS OF REMOTE SENSING APPROACH

The conventional methods, such as hydrographic surveys, are laborious, costly and time consuming. Due to these reasons, 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 major 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 very significant. Since the reservoir rarely goes below the minimum drawdown 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, 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.

Further, 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. However, if the water level information is exact and the water-spread area is interpreted accurately, it is possible to find the revised elevation-area-capacity curves quite precisely.

## CONCLUDING REMARKS

The remote sensing techniques is time and cost effective and convenient approach to estimate the elevation-area-capacity curves for a reservoir. The application of this approach has been demonstrated through a case study of Bargi reservoir. The results of the study demonstrate that the available capacity in the zone of study (406.00 m to 421.45 m) has reduced by 26.67 M Cum from the original capacity (2585.56 M Cum). The sedimentation rate in the zone of study comes out to be 0.023 ha-m/sq. km/year. The results have been compared with the CWC report of Bargi project sedimentation. In this study, the procedure to remove the discontinuous pixels and the derivation of contours has been automated to a considerable extent.

In many studies, water pixels are identified using digital processing techniques such as density slicing, classification or modelling of multi-spectral data. These techniques 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. Further, 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.

## References

Jain, Sanjay K. and Goel, M. K. (1993), "Reservoir sedimentation using digital image processing of IRS-1 LISS-I data", Proc. of National Symposium on Remote Sensing Applications for Resource Management with Special Emphasis on N.E. Region, Guwahati, Nov. 25-27, 1993, pp. 504 - 510.

Jain, Sanjay K. and Shetty, A. V. (1993), "Sedimentation of reservoir using remote sensing technique (Tungabhadra), TR-164, NIH, Roorkee.

Garde, R. J. (1995), "Reservoir Sedimentation", State of Art report of INCOH, No. INCOH/ SAR-6/95, NIH, Roorkee.

Goel, M. K. and Jain, Sanjay K. (1996), "Evaluation of reservoir sedimentation using multi-temporal IRS-1A LISS-II data", Asian-Pacific Remote Sensing and GIS Journal, Vol. 8, No. 2, Jan. 1996, pp. 39 - 43.

Goel, M. K. and Jain, Sharad K. (1998), "Reservoir sedimentation study for Ukai dam using satellite data", UM-1/97-98, NIH., Roorkee.

Gupta, S. C. (1999), "Status paper on reservoir sedimentation assessment using remote sensing techniques", Proc. of the National workshop on Reservoir sedimentation assessment using remote sensing data, May 7 – 8, NIH, Roorkee.

Manvalan, P., Rajegowda, G. L. and Srinivas, M. V. (1991), "Capacity evaluation of Ghatprabha reservoir using digital analysis of IRS LISS-II data", Project report no. B/003/91, RRSSC, Bangalore.

Morris, G. L. and Fan, J. (1997), "Reservoir sedimentation handbook – Design and management of dams, reservoirs, and watersheds for sustaiable use", Tata McGraw Hill, New York.

Narayan, D. V. V. and Babu, R. (1983), "Estimation of soil erosion in India", Journal of Irrigation and Drainage Engg., ASCE, Vol. 109, No. 4, pp. 419 – 431.

Narmada Valley Development Authority (1992), "Reservoir operation & maintenance manual", Rani Avanti Bai Sagar Project.

Rao, H. S. S. and Mahabaleswara, H. (1990), "Prediction of rate of sedimentation of Tungabhadra reservoir", International Symposium on Water Erosion, Sedimentation and Resource Conservation", October 9 - 13, 1990, Dehradun.

Shangle, A. K. (1991), "Reservoir sedimentation status in India", Jalvigyan Sameeksha, Vol.VI, No. 1 & 2, INCOH, NIH, Roorkee.

Technical Report (1981), "Sedimentation studies in reservoir", No. 20, Vol. II, CBIP, Delhi.

Varshney, R. S. (1997), "Impact of siltation on the useful life of large reservoirs", State of Art report of INCOH, No. INCOH/SAR-11/97, NIH, Roorkee.