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CAPACITY EVALUATION OF BHAKRA RESERVOIR USING DIGITAL ANALYSIS OF SATELLITE DATA

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ABSTRACT

Soil erosion, its transportation and subsequent deposition in reservoirs is a universal problem. For the operation of any reservoir, it is required to find out the reservoir sedimentation rate going on in the reservoir. During the last five decades India has constructed several major/medium river valley projects involving construction of dams and creation of reservoirs for flood controls, irrigation and hydropower etc.

Present conventional techniques of sediment quantification in a reservoir, like the hydrographic surveys and inflow-outflow methods, are cumbersome, costly and time consuming. With the introduction of remote sensing techniques, it has become very convenient to quantify sedimentation in a reservoir. With the deposition of sediments in the reservoir, the water spread area at an elevation keeps on decreasing. By comparing the decrease in the water spread area with time, the sediment distribution and deposition pattern in a reservoir can be determined indirectly. This information can be used to quantify the rate of reservoir sedimentation.

For the evaluation of sedimentation rate, Bhakra reservoir in Satluj basin has been selected for the present study. The remote sensing data of IRS-1B satellite and LISS-II sensor was acquired for different dates and the water spread areas were extracted. The post-monsoon period of the year 1988-89 and 1996-97 were chosen for the analysis. The original elevation-area-capacity curves and the reservoir levels on the eight dates of pass of satellite were obtained from BBMB, Nangal. Using the trapezoidal formula, the capacity in between the maximum (513.904 m) and minimum (472.232 m) observed levels was obtained for the year 1988-89 and maximum (510.463 m) and minimum (450.436 m) for the year 1996-97. The loss of capacity 491.315 M m^3 upto the year 1989-90 and 807.354 M m^3 upto the year 1996-97, was attributed to the sediment deposition in the zone of study of the reservoir. The results of this study have been compared with the results of hydrographic survey which was carried out in he year 1988-89.

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1.0 INTRODUCTION

1.1 GENERAL

Soil erosion, its transportation and subsequent deposition in reservoirs is a universal problem. When sediment flows into a reservoir, due to decrease in flow velocity, the coarser particles deposit first in the upper reach of the reservoir. Subsequently, the finer materials are deposited further into and along the reservoir bed. Soil is eroded due to rainfall and winds, resulting in tremendous sediment movement into the watercourses by floods and storms. Sedimentation of the reservoir is therefore a natural process resulting from the geologic and geomorphologic process of water borne erosion. Human actions can considerably hasten the natural process and increase the rate of sedimentation.

Sedimentation of reservoirs is in fact a matter of vital concern to all water resources development projects. Sediment deposition into reservoirs meant for hydropower generation has several major detrimental effects which include:

- Loss of storage capacity.
- Damage to or impairment of hydro equipment.
- Bank erosion and instabilities.
- Upstream aggradation.
- Effect on water quality.
- Effect on eutrophication.

To determine the useful life of a reservoir, it is essential to periodically assess the sedimentation rate in a reservoir. In addition, for proper allocation and management of water in a reservoir, knowledge about the sediment deposition pattern in various zones of a reservoir is essential. With the up-to-date knowledge of the sedimentation process going on in the reservoir, remedial measures can be undertaken well in advance and reservoir operation schedules can be planned for optimum utilization of water. For this reason, systematic capacity surveys of a reservoir are conducted periodically.

The reservoir surveys have been carried out using the conventional equipments e.g. theodolites, plane table, sextant, range finders, sounding rods, echo-sounders and slow moving boats etc. Most common conventional techniques for sedimentation quantification are: a) direct measurement of sediment deposition by hydrographic surveys, and b) indirect measurement 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.

1.2 SEDIMENTATION ASSESSMENT USING REMOTE SENSING

With the introduction of remote sensing techniques in the recent past, it has become convenient and far less expensive 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. Spatial, spectral and temporal attributes of remote sensing provide invaluable synoptic and timely information regarding the estimated water spread area after the occurrence of sedimentation and sediment distribution pattern in the reservoir. Multitemporal satellite data are used in determining sedimentation rate in a reservoir. It is highly cost effective, easy to use and it requires lesser time in analysis as compared to conventional methods.

The advantage of satellite data over conventional sampling procedures include repetitive coverage of a given area every few weeks, availability of 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 spatial form while the surface data collection and sampling gives point information only.

1.3 SEDIMENTATION IN INDIAN RESERVOIRS

During the last five decades, India has constructed several Major/Medium river valley projects involving construction of dams and creation of reservoirs for flood controls, irrigation and hydropower. The sedimentation survey of reservoirs in India although dates back as early as 1870, the systematic surveys started only in 1958 when the Central Board of Irrigation and Power undertook a co-ordinated scheme of reservoir sedimentation and entrusted this task to several research stations in the country. The analysis of capacity survey data of 46 reservoirs shows a wide variability in sedimentation rate of reservoirs. The sedimentation rate is affected by multiple factors like hydrometerology, physiography, climate etc. Considering these factors, the whole country has been classified into seven regions. The sedimentation rate in reservoirs in India are given region wise in Table-1 below:

Table - 1

Reservoir Sedimentation Rates in India (Moris, 1995)

Reservoir	Year of Construction	Catchment Area	Reservoir Volume (mm)	Sedimen-tation Rate (mm/year)	50% Capacity Loss (year)	Life of Reservoir (Year)
Sriramsagar	1970	91750	35	0.62	1998	56
Nizamsagar	1930	21694	39	0.64	1960	61
Matatila	1956	20720	55	0.44	2018	124
Hirakud	1956	83395	97	0.66	2030	147
Girna	1965	4729	129	0.80	2045	161
Tungabhadra	1953	28179	133	1.01	2019	132
Bhakra	1958	56980	172	0.60	2101	287
Maithon	1955	6294	218	1.43	2031	152
Lower Bhawani	1953	4200	222	0.44	2205	504
Mayurakshi	1954	1860	327	1.63	2054	201
Gandhisagar	1960	23025	336	0.96	2135	350
Koyna	1961	776	3851	1.52	3228	2533

In India, expected rates of sedimentation have been greatly exceeded. For instance, the following table shows annual rates (in acre-feet) of sediment deposit in selected reservoirs in India.

Table - 2

Status of Sedimentation Rate (acre-ft) in Various Reservoirs in India

Reservoir	Predicted Rate (Acre-ft/year)	Observed Rate (Acre-ft/year)
Bhakra	23,000	33,475
Maithon	684	5980
Mayurakshi	538	2,000
Nizamsagar	530	8,725
Panchet	1,982	9,533
Ramganga	1,089	4,366
Tungabhadra	9,796	41,058
Ukai	7,448	21,758

(Report of the Irrigation Commission from Goldsmith and Nichols)

(from Internet)

2.0 REVIEW OF LITERATURE

A number of studies have been carried out for the estimation of reservoir sedimentation using remote sensing techniques. Some of them are briefly described in the following:

Jonna et al. (1985) carried out digital image processing of remote sensing data for water quality studies. Some of the image processing techniques such as image enhancement, band ratioing, principal component analysis and unsupervised classification were applied using the IMAVISION system for the analysis of digital data of Jayakwadi reservoir.

Sahai et al. (1987) carried out a study for the Ukai reservoir for estimation of reservoir sedimentation. They investigated suspended sediment distribution in the summer monsoon and post monsoon seasons. It was concluded that sediment concentration is high along the fringe and the tail end.

Manavalan et al. (1991) evaluated the capacity of Ghataprapha reservoir using digital analysis of IRS LISS II data. The basic data extracted from satellite data were the waterspread area at different elevation levels. Density slicing on the near infrared band data was employed to obtain the water spread contours for six different reservoir levels. Water spread estimates were made by converting the water pixels into corresponding geographical area. The reduction in capacity between consecutive contour levels was computed using CONE formula and integrated to obtain the overall reduction in capacity between minimum and highest water levels.

Choubey (1992) studied the suspended sediment distribution in Tungbhadra reservoir. Data used were Landsat black and white imageries for January, April, and May. Visual interpretation technique was used. Reservoir water spread was delineated using Band 4 imageries. The suspended sediment pattern was delineated using Band 1 and 2 for January and May data. In January imageries, four levels were delineated qualitatively. These were very high, high, moderate, and low. In May imageries, three levels, namely, high, moderate and low were delineated. The suspended sediment concentration classes were found to be very high, high, moderate and low from reservoir tail to its head respectively.

Suspended sediment concentration was studied in Tawa reservoir using the satellite data and synchronous collection of field data (Choubey and Subramanian, 1992). IRS-1A LISS-I satellite data were used for September and October. Suspended sediment samples were collected from 44 locations on the day of satellite overpass from 6 AM to 7 PM. Suspended sediment concentration (SSC) was determined from all sediment samples. For selected samples, mineralogical composition was determined. It was found that SSC is high in the Denwa river segment and the main body of the reservoir. SSC decreases from reservoir tail end to its head. SSC varies between 10 to 50 ppm. DN at sample locations were averaged in 3 x 3 windows. Visible bands were highly correlated with (SSC). Band 3 had maximum variation in DN. Multiple linear regression was also fitted using several combinations of bands for October data. The best combination has two variables, namely, sum DN from Bands 1, 2 and 3 and sum of DN from Bands 1 and 3. The relationship was validated using the September data. This had overestimated SSC. It was attributed to atmospheric effect and the higher solar elevation.

Suspended sediment levels were qualitatively delineated on IRS LISS-I digital data for the Tungbhadra reservoir (Jain et. al, 1993). The data used were for the months of October, December and March. Band 1 DN values were taken as one slice to represent a concentration level of suspended sediment. Water spread area of the reservoir was delineated using Band 4.

Raju et. al (1993) carried out the field radiometric and satellite data analysis for Upper lake, Bhopal. Satellite data of TM sensor for the month of February were used. Synchronous collection of field data was completed starting two days prior to satellite overpass date. The field data were collected before noon in all days. Field radiometric data showed high correlation with total suspended sediments (TSS). TSS was in the range from 38 to 110 ppm. Only one reading of TSS was for 110 ppm. Other reading were between 38 to 70 ppm. Thus, the range of TSS was small for this study. A regression equation was fitted between radiometric Bands 1 and 2 and TSS. TSS was an independent variable in the equation. The correlation coefficient and error of estimate were respectively 0.8843 and 5.8 ppm. There was no correlation between satellite data and TSS. Satellite data were also classified into five classes using supervised method for TSS concentrations. The merging of classes was observed in the map.

Bathymetric study in Hooghly river was performed by Vinod Kumar et al. (1997) using IRS LISS-II digital data of January. At this time of the year, sediment load was less in the river. The river is fed from Farrakka barrage. The depth mapped was up to 10 m. Tidal height was

1.22 m. DN values for water were in range from 13 to 21. Sand bar had DN values 22 and 23.

George (1997) studied the lake bathymetry using airborne hyperspectral data. Data were collected in November over a turbid mesotrophic lake. The lake was clear during the data collection. The chlorophyll content was 3 μg/l. DN was converted to radiance using a spectral radiance unit (SRU) of 3.0 μ wcm^{-2} $sr^{-1}nm^{-1}$

$$\text{Radiance} = DN * SRU/255$$

It was concluded that for this lake, shorter wave lengths, e.g. blue electromagnetic radiation, were not suitable for bathymetric mapping. Differences in shallow and deep water radiance were maximum in infrared wavelengths. A dimensionless depth reflectance parameter (VR) was computed as:

$$VR = 255 * (V_s)^2/(V_d)^2$$

where

V_S is the radiance for shallow depths and

V_d is the radiance for deep water at 746 to 759 nm. The VR varies between 0 to 300 for depths 0 to 25 m.

Goel et al. (1998) carried out a study for estimation of reservoir sedimentation in the Ukai reservoir using remote sensing data. The post monsoon period of the year 1993-94 was chosen for the analysis. The remote sensing data of IRS-1B satellite and LISS II sensor was acquired for eight different dates and the water spread areas were extracted. Using the trapezoidal formula, the capacity in between the maximum and minimum observed levels was obtained. The results of the study were compared with the results of hydrographic survey which was carried out in the year 1992-93.

3.0 DESCRIPTION OF STUDY AREA AND DATA AVAILABILITY

3.1 THE STUDY AREA

For the present study, Bhakhra reservoir named also as Gobindsagar is chosen (Figure 1). This reservoir has an enormous spread of water extending over 168.35 sq km. at full reservoir level of 515.11 m. The satluj river transports a lot of silt detrimental to the life of reservoir. The silt contribution is largely due to unprecedented deforestation, over-grazing in the pasture lands, unscientific agricultural practices, indifferent contour terrace farming, absence of effective afforestation programs and other development activities undertaken in the catchment area including mining activities, road construction etc. The silt transported by river and its tributaries is deposited behind the dam in the reservoir, reducing its capacity and affecting its useful life.

3.2 AVAILABILITY OF SATELLITE DATA

Selection of appropriate period for analysis is an important step in the study of reservoir sedimentation assessment using remote sensing data. The only useful information 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 μm, 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 deposition 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 surface and consequently, the water spread area.

In India, the reservoirs generally attain the highest level near the end of the monsoon period (October - November) and then deplete gradually before the onset of next monsoon (June - July). Thus, temporal remote sensing data for any water year (October - June) 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 will be the best year 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 which is generally attained during the operation of the reservoir. It is also desirable to select the remote sensing data series of the same water year in sequence to the extent possible, and preferably, the imageries at the fortnightly intervals be used. Besides technical, there might be some administrative reasons to select the period of analysis.

In the present case, the historical record of annual maximum and minimum observed levels was available with the dam authorities, BBMB, Nangal. In the year 1988-89, maximum level at 514.499 m was observed on 13th. September, 1988. The reservoir level fell gradually till the minimum level of 464.286 m was observed on 17th. May, 1989. In the year 1996-97, maximum level at 511.771 m was observed on 22nd. September, 1996 and the reservoir level fell gradually to the minimum level of 448.75 m on 5th. June, 1997. In the present study, the analysis was carried out for both the years, i.e. 1988-89 and 1996-97.

The data of LISS-II sensor of IRS - 1B satellite, which is having good resolution of 36.25 m, was used. This multispectral data was having information of four bands which were very helpful in the identification of water spread area. The reservoir water spread area was covered in A2 quadrant of Path 30 and Row 45 of the satellite. The National Remote Sensing Agency (NRSA), Hyderabad, was contacted for enquiring about the availability of the remote sensing data for the period selected above. Due to cloud cover, some of the dates could not be obtained. The remote sensing data of following dates was procured: 1.10.88, 14.11.88, 28.12.88, 19.1.89, 10.2.89, 4.3.89, 17.4.89, 16.10.96, 7.11.96, 21.12.96, 12.1.97, and 15.6.97.

It needs to be mentioned here that for the year 1988-89, the sedimentation assessment was restricted to 513.904 m (on 1.10.88) to 472.232 m (on 17.4.89) zone of reservoir only. It is worth mentioning here that under normal circumstances, the reservoir level varies within or around this range and our main concern is to quantify the sedimentation rate and assess the sediment deposition pattern in the zone of operation (live storage).

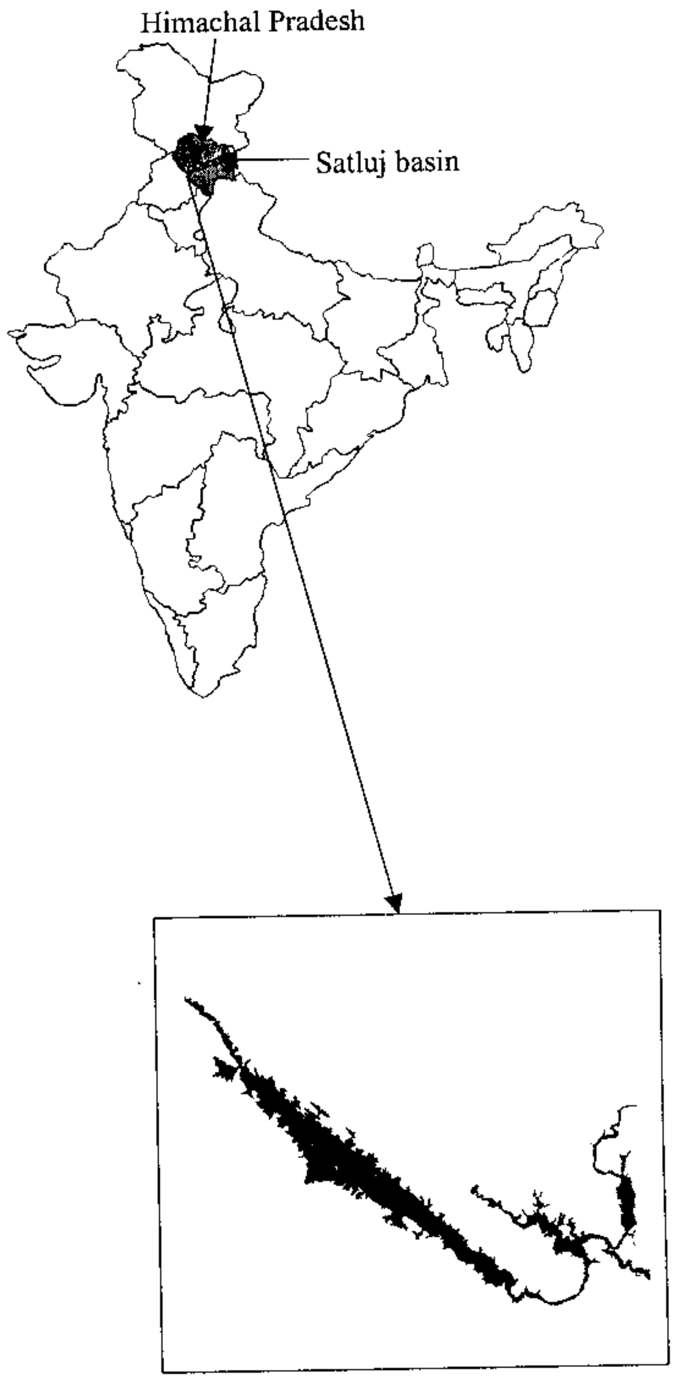

Fig. 1 The study area (Bhakra reservoir)

4.0 METHODOLOGY

4.1 GENERAL

In India, more than 80 % of the annual rainfall is received during the four monsoon months from June to September. Hence, depending on the amount of rainfall in a monsoon, water level in a reservoir can be expected to be at higher elevation after the monsoon season (September/October) before it gradually depletes to lower levels before 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 area of the reservoir at different water surface elevations.

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 during the planning and design phase of a dam. With the deposition of sediments in the reservoir, the contour (water spread) area at any elevation gradually keeps on decreasing. Greater deposition of sediments at an elevation causes greater decrease in the contour area. Revised contour areas, after the deposition of sediments, can be taken as the continuous water spread area of the reservoir having elevation as the elevation of water surface in the reservoir at the time of satellite pass. 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. The water surface elevation in the reservoir corresponding to the date of imagery and time of satellite pass can be obtained from the dam authorities. In this way, the revised contour areas at different elevations 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 trapezoidal or 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. It is important to mention here that the amount of sediments deposited below the lowest observed water level can not be determined using the remote sensing techniques. 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, it is not possible to estimate the actual sedimentation rate in the whole of the reservoir. It is only possible to calculate the sedimentation rate within the particular zone of the reservoir. However, if accurate results are required, then the hydrographic survey for the area within the lowest observed water spread area can be carried out. It is also important to emphasize here that for the purpose of optimum and judicious operation of the reservoir, the zone of interest of sedimentation analysis is only the live storage of the reservoir. Since, the reservoir hardly goes below the minimum draw down level, the interest mainly lies in knowing the loss of capacity and the pattern of sediment deposition within the live storage.

4.2 PROCESSING OF REMOTE SENSING DATA

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 interpretative 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 demarcate the water spread area. The information below the clouds can be extracted indirectly using the interpreted imageries of past and future periods and noise can be removed using different algorithms. 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. It is also easy to calculate the water spread area. For these reasons, digital techniques are superior and are gaining recognition now-a-days. In this study, digital analysis was carried out for identifying the water pixels and for determining the water spread area. The various steps followed in the analysis are described below:

4.2.1 Import and Visualisation

The data of IRS-1B satellite and LISS-II sensor for two years 1988-89 and 1996-97 were received from NRSA on the CD-ROM media. The dates of these data are already given. The data were processed and analysed using the ERDAS/IMAGINE 8.3.1 software. The data were loaded on the computer from the CD-ROM and was imported in the ERDAS system. Each scene was having 2500 rows, 2520 columns and the information of four bands (three visual and one near-IR). There were no header bytes in the data. Imageries of all the dates were imported and stored in the hard disk. Reservoir water spread was mostly covered in lower right quadrant of the full scene.

Initially, a false colour composite of 4, 3 and 2 Bands combination was prepared and visualised. Then, each individual band was visualised one by one. It was found that the bands, as specified by the NRSA, do not represent the true bands. In all the scenes, it was found that Band 1 represents actual Band 4 (0.77 - 0.86 μm), Band 2 represents actual Band 1 (0.45 - 0.52 μm), Band 3 represents actual Band 2 (0.52 - 0.59 μm) and Band 4 represents actual Band 3 (0.62 - 0.68 μm). This identification was based on the standard spectral signatures of water and vegetation. So, the standard FCC (combination 4, 3 and 2) was prepared using 1, 4, 3 combination. The pixels representing water spread area (except at the periphery) of the reservoir were quite distinct and clear in the FCC.

4.2.2 Geo-referencing

While using the temporal satellite data of the same area, it is required to geo-reference the imageries of different time periods. Using geo-referenced imageries, overlaying of different scenes and detection of land use/land cover changes can be made.

In the present case, detection of land use change was not the objective. Further, the determination of the water spread area did not require the geo-referencing of the different scenes. However, using the geo-referenced imageries, it was possible to overlay the remote sensing data of different dates, to compare the change in the water spread area and to observe the shrinkage in the water spread with time, particularly the tail end of the reservoir. Using the geographic water spread information, revised contours (as prevailing in the present condition after sedimentation) can also be prepared by vectorization of the raster water spread data and the DEM of the gorge can be generated. Using the revised and the original DEM, the depth of sediment deposited at any point can be determined.

The imagery of October, 1988 was considered as the base (master) since it was very sharp and clear and cloud and noise free. The imageries of other dates were considered slaves and geo-referenced with the master. In the ERDAS/IMAGINE, a number of viewer windows can be opened at the same time and in the present case, two such windows were opened. In these windows, one master image and one slave image was displayed. Some clearly identifiable features like crossing of rivers, canals, sharp turns in the rivers, dam, bridges etc. were located on both the images and were selected as control points. About 10 such points were selected for geo-referencing in all the cases. Now looking at the statistics, some points which generated big errors were deleted and replaced by other points so as to obtain the satisfactory geo-referencing. In this manner, all the available images were geo referenced. After completing this process, different images were displayed one over the other and the superimposition was compared. The geo-referencing was found to be satisfactory.

4.2.3 Separation of Area of Interest (AOI)

Since the size of each full scene was very large and our area of interest was only the reservoir spread area, the reservoir area and its surrounding was separated out from the full scene in all the imageries. This was done through a utility named area of interest (AOI). A polygon was constructed which covered the reservoir spread area and some area adjacent to it. Now the data corresponding to this AOI polygon was saved in a new file and similar procedure was repeated for all the imageries by using the same AOI. Separation of the area of interest from the full scene resulted in less consumption of computer space, easy handling of files and appreciable reduction in the analysis time. This also reduced the efforts for editing the files at the later stage.

4.2.4 Identification of Water Pixels

This was the basic interpretation factor from the remote sensing data. 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 interpretative 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 spread area. Secondly, it is also possible that a pixel, only at the soil/water interface, may represent mixed conditions (some part as water and other part as soil).

In the visible region of the electromagnetic spectrum (0.4 - 0.7 μm), 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 act 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 μm) onwards. Beyond Band 2, with increase in wavelength, water reflectance curves show downward trend while soil/vegetation curves show upward trend. This characteristic was mainly used to differentiate the exclusive water pixels from other pixels in all the imageries.

Different techniques were tried to distinguish and separate out the water pixels. Density slicing of the near-IR band was carried out and compared with the standard FCC. Though most of the water pixels could be accounted for by this technique, it was not considered to give exclusive water pixels in a satisfactory way. The sliced pixels may include some saturated soil pixels also as the reflectance value of saturated soil is very low in the near-IR band. Supervised classification is another way of identification. Though clearly distinguishable water pixels could be easily separated out by this technique, accurate training sets for peripheral pixels could not be given. A generalised algorithm, based on the information of different bands, was used for differentiation of water pixels.

Using the spectral information, the algorithm matches the signatures of the pixel with the standard signatures of water and then identifies whether a pixel represents water or not. The algorithm checks for one condition for each pixel and if a pixel satisfies the conditions, then it is recorded as a water pixel, otherwise not. The condition states that "If the DN value of near-IR band of the pixel is less than the DN value of the 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 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 Band 4 will cause 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. So, this condition differentiates the water pixels exclusively from other pixels.

The condition was applied in the form of a model in the ERDAS/IMAGINE software and the model runs were taken. This condition was employed to differentiate the water pixels in all the imageries. The resulting imagery of water pixels from this method was compared with the near-IR imagery and the standard FCC. The results were found to be satisfactory in all the cases. The biggest advantage of using this method was that it avoided the necessity of selecting different limits as is required in NDVI or density slicing. Selection of different limits in different imageries can cause some non-water pixels to be selected or some water pixels to be rejected.

There was possibility of some error in the interpretation because of the presence of mixed pixels along the periphery of the spread area. However, depending on the area covered by the water or soil in a mixed pixel, classification of some pixels as exclusively water and some as exclusively soil can mutually counterbalance the effect of misclassification to some extent. It was not possible to confirm the results of remote sensing interpretation from the field because the data pertained to the years 1988-89 and 1996-97 and no field data, regarding the actual spread area on dates of satellite pass, were available. Even if the study is to be planned for future, it is very difficult to collect and demarcate the exact periphery of the water spread on a single day using conventional ground methods. The only possible way can be to make simultaneous observations from the satellite and aerial platforms.

There was no cloud cover or noise in the imageries. However, the images of water spread as obtained from the interpretation, were edited to remove the isolated water pixels, and extension of tail and adjoining rivers around the water spread.

The main objective of calculating the water spread area was to determine the revised contour area at the elevation of the water surface. Since the contour area represents the continuous area, it required that the isolated water pixels that surround the water spread area and that are located within the islands, must be removed from the interpreted image.

As the water level falls, small islands appear within the reservoir area. The size of these islands keeps on increasing as the water level goes down. Due to the presence of local depressions within the islands and around the periphery of the reservoir, a few pixels within the depressions appear to be water pixels. These pixels do not form part of the continuous water spread and were removed by copying the non-water pixels over these water pixels.

5.0 ANALYSIS AND RESULTS

5.1CALCULATION OF SEDIMENT DEPOSITION

To study and compare the actual silt deposits vis-à-vis the project assumptions, capacity surveys are carried out annually from 1963 to 1977 and thereafter these surveys are being carried out every alternate year. The last survey was carried out during Oct.1996 to March, 1997. Original elevation-area-capacity data of Bhakra was taken from the report prepared by Water and Power Consultancy Services (India) Limited and it is presented in tabular form in Table-3 below. The surveys have been carried out by observing the soundings along predetermined cross sections, approximately 6-10 m apart, by means of echo sounder. These results are super-imposed on the results of previous survey for working out the quantity of silt deposited at each cross section in the whole reservoir.

Table 3 : Original Elevation-Area-Capacity Table for Bhakra Reservoir

Reservoir Elevation (m)	Area (Mm^2)	Capacity (Mm^3)
515.11	168.67	9867.86
513.58	165.92	9621.15
512.07	162.48	9346.62
505.97	149.93	8363.01
499.87	137.83	7462.56
493.78	125.04	6673.13
487.68	113.91	5957.71
481.59	103.19	5248.46
475.49	94.49	4687.23
469.39	85.99	4144.49
463.30	78.30	3642.24
457.20	71.46	3120.70
451.11	60.70	2781.50
445.01	59.00	2392.95
438.92	54.02	2053.75
432.32	49.29	1736.74
426.72	45.52	1443.17

The reservoir elevations at the time of satellite pass were obtained from BBMB, Nangal. The revised areas and the corresponding elevations are presented in Table - 4 for both the years i.e. 1988-89 and 1996-97. The imageries of different dates showing the FCC and the final water spread area are presented in Figures 2 to 7 for the year 1988-89 and in Figures 8 to 13 for the year 1996-97.

Table 4 : Reservoir Elevation & estimated Area on the Date of Satellite Pass

Date of Pass	Number of Water Pixels	Reservoir Elevation (m)	Water spread Area Using Remote Sensing (M m^2)
1/10/88	110736	513.904	145.514
14/11/88	108537	511.818	142.6244
28/12/88	105000	504.964	137.976
19/1/89	104079	501.990	136.766
10/2/89	93692	496.281	123.117
4/3/89	78935	487.679	103.72
17/4/89	55982	472.231	73.56
16/10/96	106303	510.463	139.688
7/1196	105120	506.212	138.134
21/12/96	90411	494.622	127.472
12/1/97	76005	487.734	108.994
15/6/97	37147	450.436	48.813

The reservoir capacity between two consecutive reservoir elevations was computed using the trapezoidal formula:

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

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.

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 estimated capacities were worked out as mentioned above. The cumulative estimated capacity of the reservoir at the lowest observed level (472.232 m) was assumed to be the same as the original cumulative capacity (4415.86 Mm^3) at this elevation before the construction of the dam. Above the lowest observed level, the cumulative capacities between the consecutive levels were added up so as to reach at the cumulative original and estimated capacities at the maximum observed level. The difference between the original and estimated cumulative capacity represents the loss of capacity due to sedimentation in the zone under study. The calculations of sediment deposition for the year 1988-89 and 1996-97 are presented in Table -5 and 6 respectively. The results show that the volume of sediment deposition during 1965 to 1988-89 (24 years) in-between the maximum and minimum observed levels (513.904 m and 472.232 m) is 491.315 Mm^3 . For the period upto 1996-97 i.e. for 32 years period the volume of deposition in-between the maximum and minimum observed levels (510.463 m and 450.436 m) works out to be 807.354 Mm^3. If the uniform rate of sedimentation is assumed, then as per the 1988-89 analysis, the sedimentation rate in the zone (513..904 m to 472.232 m) is 20.47 M m^3 per year. As per the 1996-97 analysis, the rate of sedimentation in the zone (510.463 m to 450.436 m) comes out to be 25.23 M m^3 per year.

Table - 5 : Calculation of Sediment Deposition in Bhakra Reservoir Using Remote Sensing for the year 1988-89

Date of Satellite Pass	Reservoir Elevation (m)	Original Area (Mm^2)	Estimated Area (RS) (Mm^2)	Original Volume (Mm^3)	Estimated Volume (RS) (Mm^3)	Original Cumulative Volume (Mm^3)	Estimated Cumulative Vol. (RS) (Mm^3)
1/10/88	513.904	166.62	145.52			9656.178	9164.864
				342.563	300.552		
14/11/88	511.818	161.80	142.63			91313.616	8864.31
				1064.119	961.484		
28/12/88	504.964	148.83	137.98			8249.497	7902.827
				432.658	408.507		
19/1/89	501.990	142.18	136.77			7816.839	7494.32
				780.062	741.574		
10/2/89	496.281	131.14	123.12			7036.770	6752.706
				1057.294	974.317		
4/3/89	487.679	113.53	103.72			5985.483	5778.429
				1569.623	1312.942		
17/4/89	472.232	90.13	73.56			4415.86	4415.86

Table - 6 : Calculation 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)	Estimated Area (RS) (Mm^2)	Original Volume (Mm^3)	Estimated Volume (RS) (Mm^3)	Original Cumulative Volume (Mm^3)	Estimated Cumulative Vol. (RS) (Mm^3)
16/10/96	510.463	158.364	139.688	657.322	590.807	8745.836	7938.482
7/11/96	506.212	150.406	138.134			8088.575	7347.675
				1603.107	1487.525		
21/12/96	494.622	126.572	118.80			6485.408	5860.15
				828.016	752.157		
12/1/97	487.734	113.998	99.87			5657.392	5108.0
				3264.892	2716.47		
15/6/97	450.436	63.538	48.813			2392.950	2392.95

5.2 COMPARISON OF RESULTS WITH HYDROGRAPHIC SURVEY

BBMB has carried out regular hydrographic surveys in the reservoir area. These have been done by taking vertical cross sections across the river. The Empirical Area Reduction method requires areas in horizontal planes. This data is available only at the beginning of the project, i.e. 1965. Therefore, the EAR method was applied to 1965 E-A-C curve to predict sediment deposition pattern for 1988. The sediment volume to be distributed was taken as the actual sediment volume measured in 1988 hydrographic survey. The results are shown in Table-7. The elevation-capacity graph of this theoretical distribution pattern for 1988 was superposed on the elevation-capacity graph for observed 1988 data.

Table 7: Revised Elevation-Capacity Table for Bhakra Reservoir
(Results of Hydrographic Survey of 1988-89)

Reservoir Elevation (m)	Area (Mm^2)	Capacity (Mm^3)
515.11	168.67	8815.09
513.58	163.55	8570.18
512.07	159.38	8299.78
505.97	145.21	7340.00
499.87	132.16	6471.26
493.78	118.68	5718.48
487.68	107.03	5043.44
481.59	95.90	4377.33
475.49	86.88	3861.53
469.39	78.13	3365.97
463.30	70.26	2912.37
457.20	63.28	2440.10
451.11	52.43	2150.99
445.01	50.69	1813.01
438.92	45.71	1524.43
432.32	41.02	1258.00
426.72	37.33	1014.63

The cumulative capacity at the lowest observed level was assumed to be equal to that of hydrographic survey and the cumulative capacity at the highest observed level was obtained. This was compared with results of hydrographic survey. The calculations are presented in Table - 8.

Table - 8 : Comparison of Results of Hydrographic Survey with Remote Sensing

Date of Satellite Pass	Reservoir Elevation (m)	Original Volume (Mm^3)	Estimated Volume (RS) (Mm^3)	Original Cumulative Volume (Mm^3)	Estimated Cumulative Vol. (RS) (Mm^3)
1/10/88	513.904			8562.987	8362.753
		336.448	300.552		
14/11/88	511.818			8226.739	8062.201
		1031.561	961.484		
28/12/88	504.964			7195.178	7100.717
		416.702	408.507		
19/1/89	501.990			6778.476	6692.21
		742.796	741.574		
10/2/89	496.281			6035.679	5950.636
		978.035	974.317		
4/3/89	487.679			5057.644	4976.319
		1443.894	1312..942		
17/4/89	472.232			3613.75	3613.75

For the year 1988-89, the estimated capacity (9164.869 M m^3) was subtracted from the original capacity (9656.178 M Cum) and the loss in capacity (491.315 M m^3) was attributed to the sediment deposition in the zone of study (513.904 m to 472.232 m) of the reservoir. The hydrographic survey of the reservoir was carried out in the year 1989-90. As per the results of this survey, the estimated capacity of the zone under study comes out to be 4949.237 M Cum with an average capacity loss rate of 12.65 M Cum per year. This value is appreciably lower than what was found from the remote sensing analysis (20.47 M m^3). The reason for this is explained as follows. In computing the capacity using remote sensing analysis, water spread area was calculated from satellite data. The level corresponding to the date of pass was collected from the project authority. The hydrographic survey data for the year 1988-89 was taken from WAPCOS report. In the report the levels are not the same as taken for remote sensing data. Therefore for calculation of the area and thus capacity according to the dates of satellite pass, was made from interpolation of the levels available from hydrographic survey and this may result in descrepancy in the calculation of the area. The other reason for the difference in the sedimentation rate may be due to missing of some part at the tail end in the satellite imagery of

December, 1996. In the image of December 1988, a part at the tail end is not covered in the satellite pass and hence in calculation of the water spread area that part is not accounted for. The reduction is water spread area correspondingly results increase in sedimentation volume.

As mentioned earlier that the capacity surveys have been carried out annually from 1963 to 1977 and thereafter these surveys are being carried out on alternate year. The last survey was carried out during 1996-97. The sedimentation studies report prepared by Bhakra Beas Management Board (BBMB) was collected from BBMB, Nangal. According to this report, the average annual rate of siltation has been worked out as 34.33 Mm^3 for the years from 1965 to 1996 against a designed figure of 33.61 Mm^3. According to this report, the average annual rate of siltation has been worked out as 34.33 Mm^3 for the years from 1965 to 1996 against a designed figure of 33.61 Mm^3. In this report the result of the sedimentation survey for dead and live load are given separately. The results of the survey for the year 1996-97 are given in the following table.

Table: 9 Results of Hydrographic survey (1996-97)

Original designed capacity (1965)			Capacity at the end of 1996-97		
Dead stoarge (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

From the table it is clear that the loss in dead storage and live storage is almost same. In the present study , the analysis has been made only for live storage of Bhakra reservoir, therefore, the results of hydrographic survey for sedimentation in live storage were considered. The Table 9 shows that as per the hydrographic survey, the loss of live storage from 1965 to 1997 i.e. for a period of 32 years is 666.073 Mm^3, thus average sedimentation rate in this zone is 20.81 Mm^3 per year. For the year 1996-97, the estimated capacity, using remote sensing technique, (7938.482 Mm^3) 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 capacity in the study is computed to be 25.23 Mm^3 per year.

The plot of original and estimated cumulative capacity as derived using remote sensing technique is shown in Figures 13 and 14 for the year 1988-89 and 1996-97 respectively. The plots of the estimated cumulative capacity as per the Hydrographic study and as per the remote sensing analysis for the year 1988-89 is presented in Figure 15 .

5.3 DISCUSSION OF RESULTS

It is seen that the estimation of sedimentation by remote sensing is highly sensitive to the accurate determination of water spread area. In the present case, an error of 1% in the estimation of water spread area would result in the sedimentation difference of 48 M m^3. Though every effort has been made to estimate the water spread area as precisely as possible and uniform method of analysis has been adopted for all the imageries, yet the difference is equivalent to approximately 4% error in the area estimation. Some of the reasons for the difference between the two results can be either or a combination of the following:

a) Difference in the method adopted for the calculation of cumulative capacity in both the techniques. In the present study, trapezoidal formula has been used for the capacity determination between two contours and actual contour areas have been considered rather than considering the areas from the smooth curve of best fit.

b) Different criteria of demarcating the tail end of the reservoir. In the present study, the tail has been truncated at the termination point of water spread. In almost all the dates of atleast upto December, when water spread area is more, some part at the tail end is not covered in the path/row obtained from NRSA. Extension of the tail end can result in the increase in spread area and the subsequent lesser volume of sediment deposition.

c) Mixed pixels having larger proportion of land and smaller proportion of water around the periphery of the reservoir.

d) In the image of December , 1988, the small storage upstream of the main reservoir was missing and therefore the area in this particular image represented the area of the main reservoir only.

e) This is a particular reservoir consisting of two parts comprising of main reservoir and a small storage upstream of main reservoir. Both these storage are connected through a small stream. Since the main inflow in the Bhakra reservoir enters only after passing the small storage, most of the sediment deposition takes place in the small storage only without causing appreciable reduction in the area of main reservoir. Therefore, it is desirable to quantify the sedimentation rate in the small storage only. However, separate hydrographic survey results were not exclusively available for a small storage. Hence, this study was carried out for the full extent of water spread area. It is however, felt that frequent hydrographic survey must be carried out for the small storage while for the main reservoir the frequency of survey can be reduced.

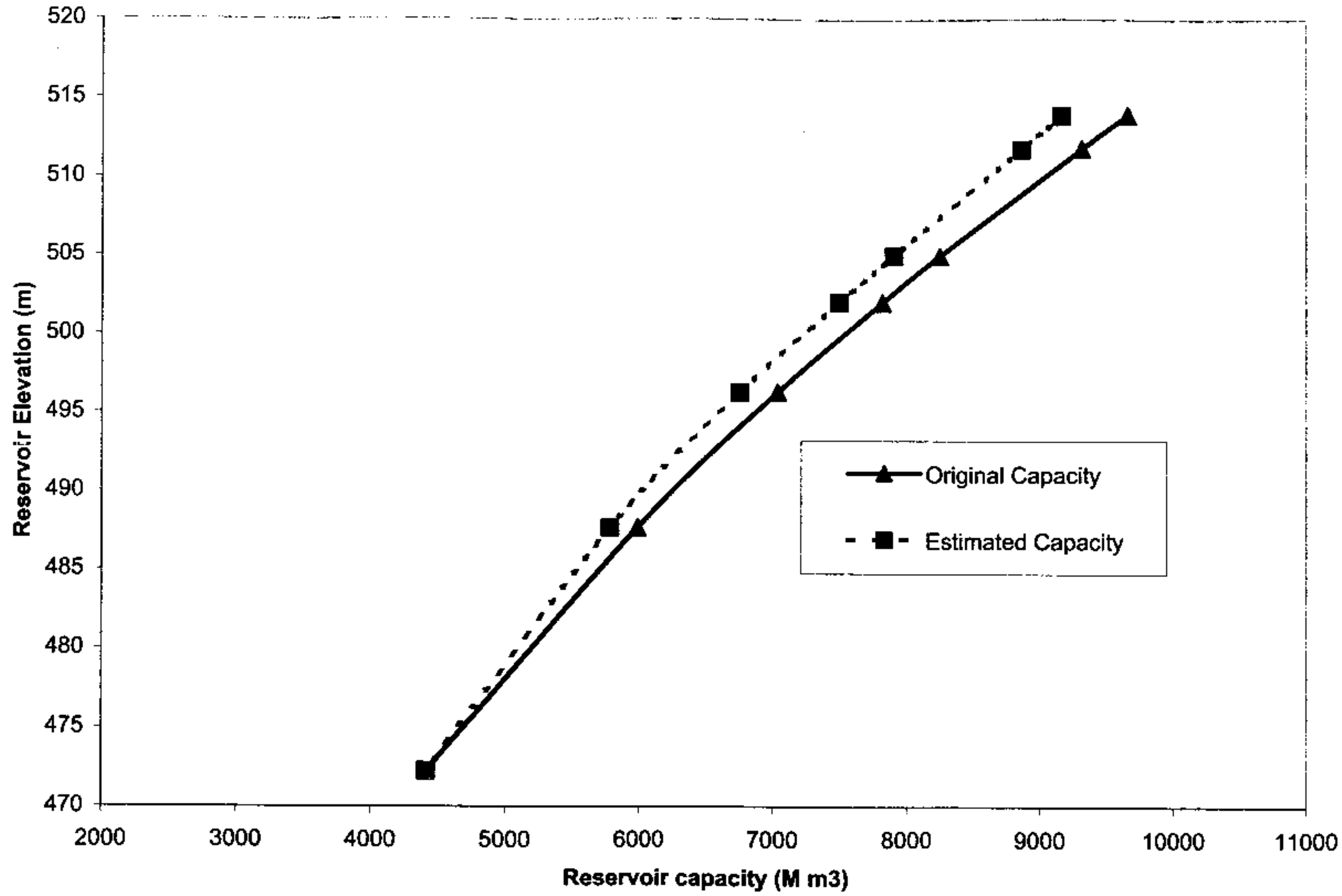

Fig. 13 : Elevation- capacity curves for Bhakra reservoir (1988-89)

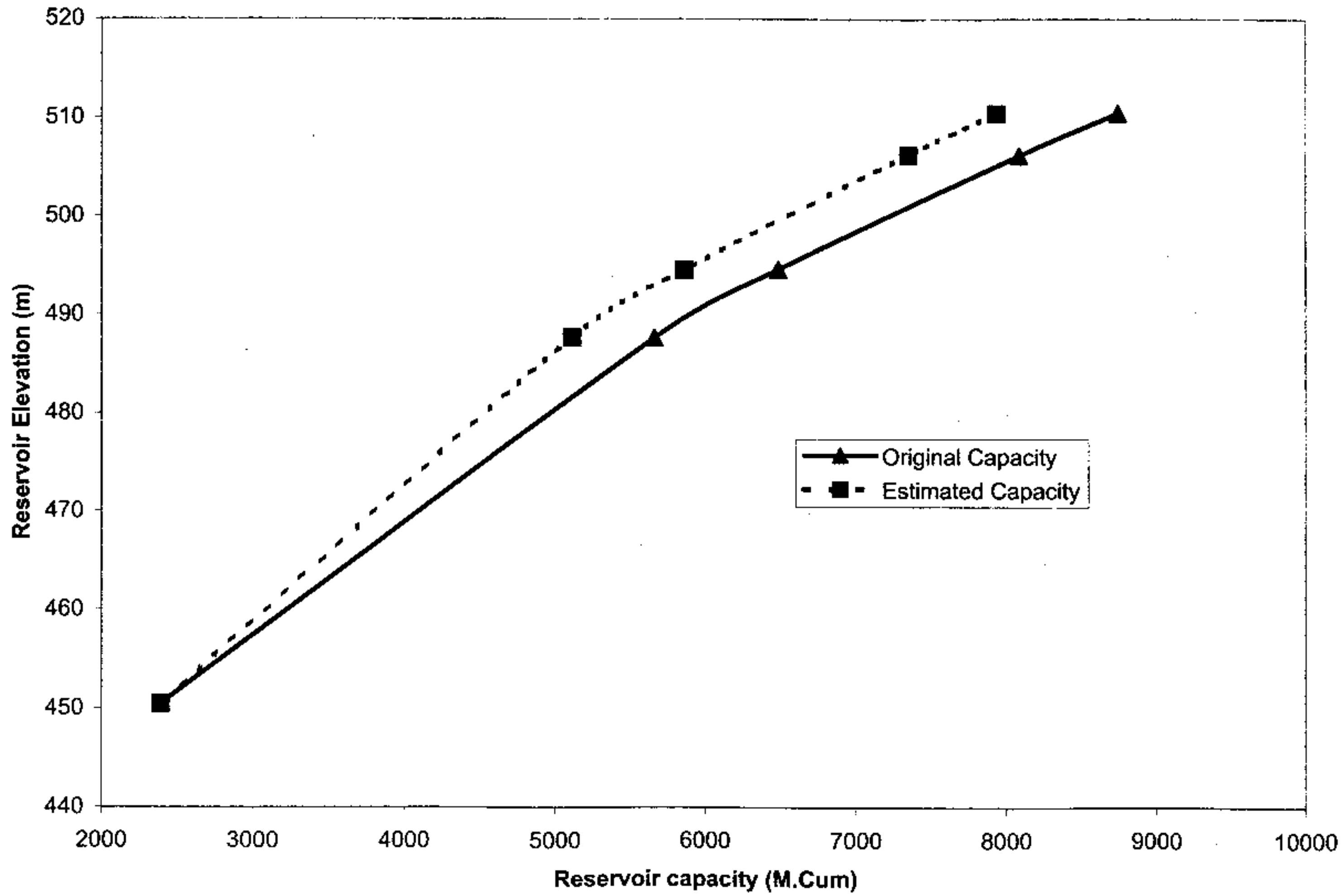

Fig. 14: Elevation- Capacity Curves for Bhakra reservoir (1996-97)

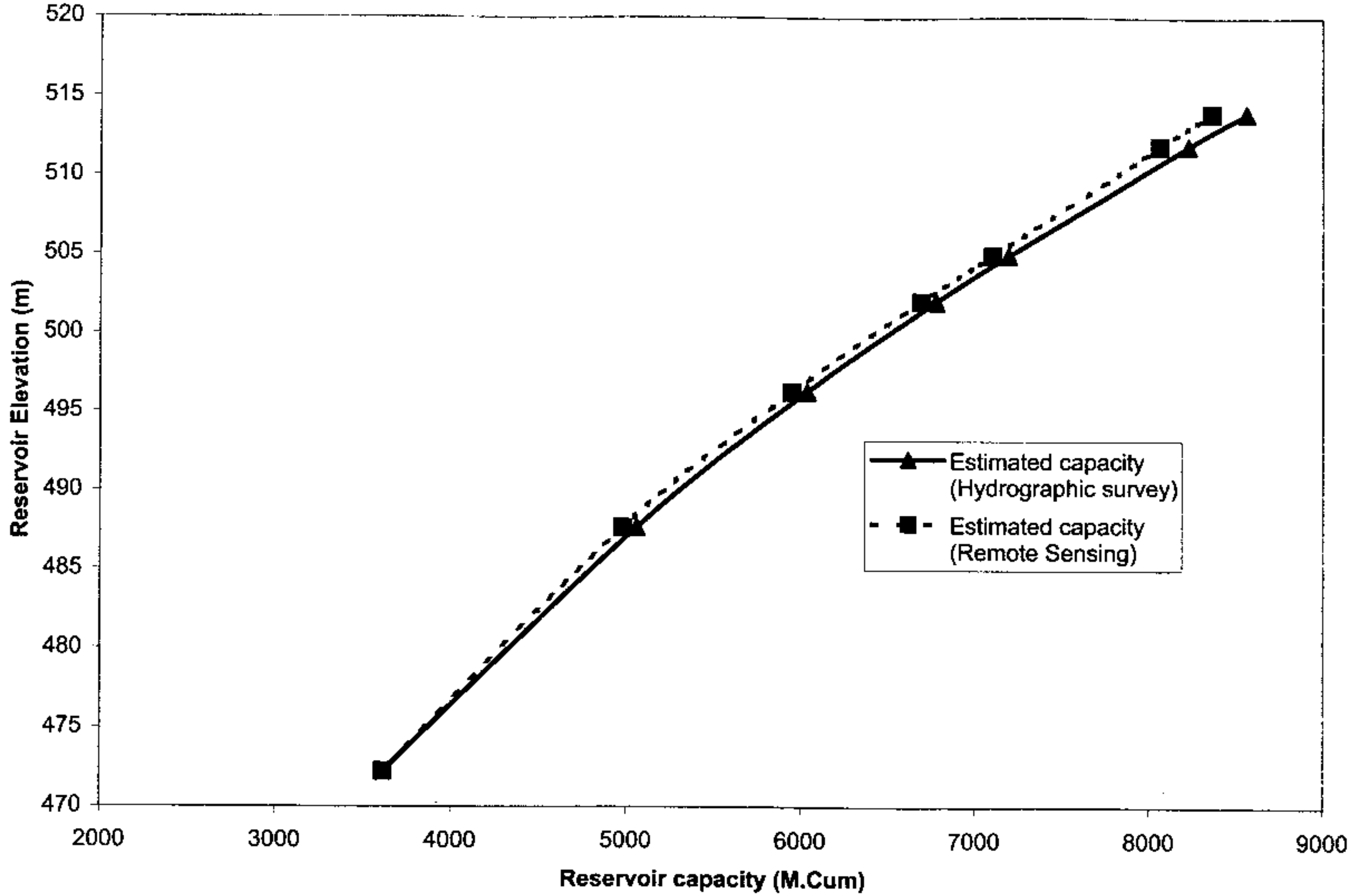

Fig. 15 : A comparison of the results obtained through remote sensing technique and hydrographic survey

6.0 CONCLUSION

For taking remedial measures well in advance and for optimum allocation and management of water from the reservoirs, it is very essential to have up-to-date knowledge about the sedimentation pattern going-on in the reservoir and the loss of capacity because of sediment deposition in the various zones. Satellite remote sensing by virtue of its synoptic coverage and repetitivity is found to be very useful in capacity surveys of the reservoirs. Its multi date data directly provides the elevations contours in the form of water spread area.

In the present study, the sedimentation rate and volume was determined in the Bhakra reservoir using the remote sensing data. Remote sensing data of IRS-1B satellite and LISS-II sensor was acquired for the years 1988-89 and 1996-97 and the estimated water spread area was extracted. The original elevation-area-capacity curve and the reservoir levels on these years for the dates of pass of satellite were obtained from the dam authorities. Using the trapezoidal formula, the estimated capacity in between the maximum and minimum observed levels was obtained. For the year 1988-89, the estimated capacity (9164.863 M m^3) was subtracted from the original capacity (9656.178 M m^3) and the loss in capacity (491.315 M m^3) was attributed to the sediment deposition in the zone of study (513.904 m to 472.232 m) of the reservoir. Thus, the average rate of loss of capacity in this zone came out to be 20.47 M m^3 per year. For the year 1996-97, the estimated capacity (7938.482 M m^3) was subtracted from the original capacity (8745.836 M m^3)and the loss in capacity (807.354 M m^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 capacity in this zone came out to be 25.23 M m^3 per year.

The hydrographic survey of the reservoir was carried out in the year 1989-90. As per the results of this survey, the estimated capacity of the zone under study comes out to be 4949.237 M m^3 with an average capacity loss rate of 12.65 M m^3 per year. This value is appreciably lower than what was found from the remote sensing analysis. Some possible reasons for this difference have been discussed in the report. It was seen that the remote sensing method of determining sedimentation is highly sensitive to the interpretation of the water spread area. For the present study, it was estimated that 1% change in the interpretation of water spread area can result in change of sedimentation volume by about 48 M m^3. In remote sensing analysis, various factors which can cause difference in the calculation of the water spread area include: i) clouds and noise in the data, ii) number of mixed pixels, and iii) the method of analysis. The selection of tail end is also based on subjective interpretation and can influence the results. However, the use of better resolution (spatial and temporal) satellite data can be a remedy for these problems to some extent.

Satellite remote sensing based survey gives the information on the capacities in the water level fluctuation zone or in other words in live zone only of the reservoir. In the dead zone, the information on the capacity could be taken from the most recently conducted hydrograhic survey. Use of satellite remote sensing technique enables a fast and economical estimation of live storage capacity loss due to sedimentation. 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.

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