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LECTURE NOTE

REMOTE SENSING APPLICATION IN RESERVOIR SEDIMENTATION STUDIES

By

SANJAY K. JAIN
NIH, ROORKEE

NATIONAL INSTITUTE OF HYDROLOGY
JALVIGYAN BHAWAN
ROORKEE – 247 667 (UTTARAKHAND)

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

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

1.0 RESERVOIR SEDIMENTATION

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

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

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

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

The sediment deposits in a reservoir can be divided in three groups: topset beds, foreset beds, and bottomset beds (Fig. 1).

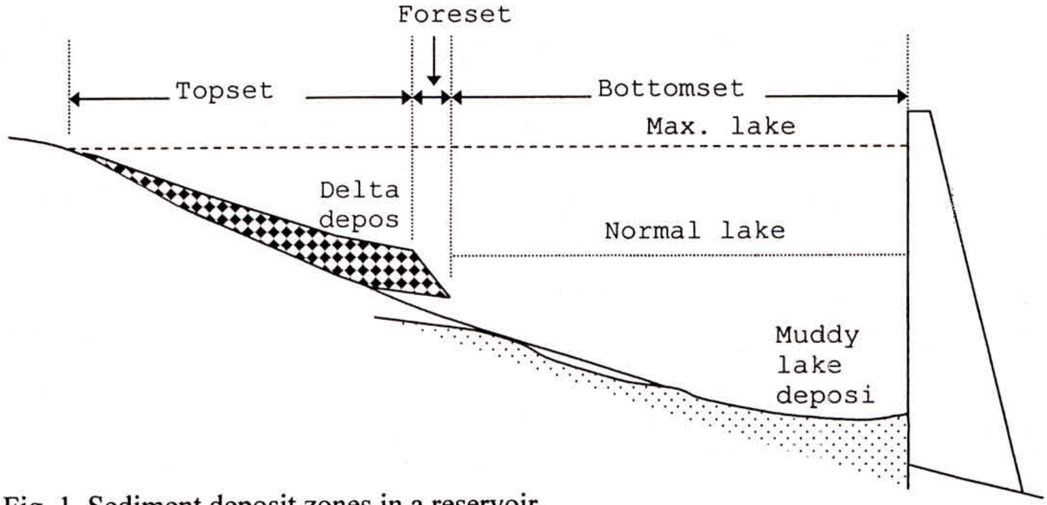

Fig. 1 Sediment deposit zones in a reservoir.

The topset beds are composed of large size sediment deposits but may also have fine particles. These extend up to the point where the backwater curve ends. The downstream limit of the topset bed corresponds to the downstream limit of bed material transport in the reservoir. These deposits cause minor reduction in the reservoir storage capacity. Foreset deposit is the face of the delta deposit advancing towards the dam. It is a transition zone having steeper slopes and decreasing grain size. The bottomset beds consist of fine sediments, which are deposited beyond the delta by turbidity currents or non-stratified flow. This scene of deposits may change due to reservoir drawdown, slope failures and extreme floods.

For proper reservoir management, knowledge about the sediment deposition pattern in various zones is essential. Timely remedial measures can be undertaken with the correct knowledge of the sedimentation processes in a reservoir.

2.0 RESERVOIR SURVEYS

Sediments accumulated in an existing reservoir can be determined by periodically running sediment surveys. It is a direct measurement procedure to assess the volume and pattern of deposits. Sediment data collected during the surveys are analyzed to determine the specific weights of the deposits, their grain size distribution, sediment accumulation rates, and reservoir efficiencies. Recent advances in technology have considerable reduced the efforts to carry out reservoir surveys and analyze data.

The accuracy of these surveys is usually very high particularly if advanced equipment are used. It is possible to estimate the total sediment (bed and suspended) load being carried by the river. But such surveys do not provide any information about the variation of sediment yield with time and give only the total sediments accumulated since the last survey. This method does not provide sub-catchment wise sediment yield. Finally, to find the total sediment inflow, the information about sediment outflow is also needed.

The frequency of surveying the reservoirs depends on the sediment accumulation rate and cost of running a survey. Reservoirs with high accumulation rates are surveyed more often than those with lower rates. Generally, the reservoirs are surveyed every 3 to 10 years. Special circumstances may necessitate a change in the established schedule. A reservoir might be surveyed after a major flood that has brought in heavy sediment load. A survey may also be run following the closure of a major dam constructed upstream in the same catchment. An upstream dam reduces the free drainage area and hence reduction in the sediment inflow.

3.0 REMOTE SENSING APPROACH TO ASSESS RESERVOIR SEDIMENTATION

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

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

3.1 Selection of Period of Analysis

This is an important step in carrying out the analysis for reservoir sedimentation assessment using remote sensing data. The pertinent information, which is extracted from the remote sensing data, is the water spread area at different dates of pass of the satellite over the reservoir area. Though in the wavelength region 0.45 - 0.52 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 deposited in the reservoir.

Therefore, it is imperative to use the remote sensing data of such a period when there is maximum variation in the elevation of the reservoir water level.

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

3.2 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:

IRS - 1A/ IRS - 1B [LISS-I (72.5 m) & LISS-II (36.25 m)]
b) IRS - 1C /1D [PAN (5.8 m) & LISS-III (23.5 m)]
c) LANDSAT [MSS (80 m) & TM (30 m)]
d) IRS-P6 (RESOURCESAT-1)
e) IRS-P5 (CARTOSAT-1)
f) SPOT satellite

Multi-spectral information is required for the identification of water pixels and for differentiating the water pixels from the peripheral wet land pixels. It is also desirable to use the data of higher resolution for obtaining accurate results. However, the use of PAN sensor data is not usable because it lacks spectral information. IRS-1C satellite was launched in the year 1995 and IRS 1D was launched in 1997. Thereafter, India has launched IRS-P6 and IRS-P5, in which P5 is having even higher resolution of 2.5 m. At present, the remote sensing data of IRS satellites is the best selection in India from the cost and resolution considerations.

Multi-spectral data are required for identification of water pixels and to differentiate the water pixels from the peripheral wetland pixels. It is necessary to ascertain that good quality cloud free satellite data are available. It is also desirable to use high-resolution data for better results. The data of a number of satellites are available these days and a choice is usually made based on the frequency of satellite pass, spatial resolution, and cost considerations. These days, satellite data are mostly supplied on CD-ROM and Internet is being increasingly used for this purpose.

3.3 Identification of Water Pixels

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

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

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

3.4 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:

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

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

3.4 CASE STUDY OF MATATILA RESERVOIR

Matatila Dam was constructed in the year 1956 across river Betwa that is tributary of the Yamuna River. The dam lies at 25^{O} 6'15" North Latitude and 78^{O} 23'00" East Longitude. It is located at Matatila in District and Tehsil Lalitpur of U.P., which is 56 km. from Jhansi. It is situated 4.8 km southwest of Basai railway station on the left bank of Betwa River, and 11.25-km. northwest of Talbehat railway station on the Right Bank.

A number of Hydrographic surveys in Matatila reservoir have been conducted so far by U.P. Irrigation Research Institute, Roorkee in pre monsoon period of the year 1962, 1964, 1966, 1969, 1971, 1975, 1975, 1985 and 1990.

The first capacity survey of Matatila reservoir was conducted before the monsoon of 1962, when the reservoir was practically empty. The gross capacity and dead storage capacity were worked out to 985.71 Million m^3 and 109.02 Million m^3 whereas its original gross and dead storage capacity as per project report are 1132.70 Million m^3 and 113.30 Million m^3 respectively. Because the capacity for the project purpose was estimated earlier in 1956 on the basis of inadequate survey, the gross capacity of 985.71 Million m^3 has been taken as the basis for the purpose of determining the loss in capacity in subsequent years. The streambed elevation, as per 1962 survey was 280.40m. The same has been used in the present study also for determining losses etc.

The gross and dead storage capacity in 1975 reduced to 882.87 Million m^3 and 52.06 Million m^3. The 1975 hydrographic survey indicated a total capacity loss of 10.43% of its 1962 pre-monsoon capacity, indicating an average reduction of 0.8% per year. Average sedimentation index was worked out as 381.8 m^3/sq.km. /year against the assumed value in the design being 132 m^3/sq.km. /year. The new zero elevation was worked out as 286.16m. It was also estimated that the reservoir would be filled up to dead storage level by the year 1996.

As per the hydrographic survey in pre monsoon period of the year 1985, the gross capacity and dead storage capacity were worked out to 784.30 Million m^3 and 35.71 Million m^3 respectively. The new zero elevation was worked out as 286.60m. The total loss in capacity was 20.43% in 23 years of its 1962 pre-monsoon capacity, which indicated an average reduction of 0.89% per year. The average sedimentation index was worked out as 422.63 m^3/sq.km./year.

The gross and dead storage capacity in 1990 reduced to 748.72 Million m^3 and 25.49 Million m^3. The 1990 hydrographic survey indicated a total capacity loss of 24.04% of its 1962 pre-monsoon capacity, indicating an average reduction of 0.86% per year. Average sedimentation index was worked out as 408.50 m^3/sq.km./year.

One more hydrographic survey in Matatila reservoir was conducted in 1994 by Minor Ports Survey Organisation, a service organisation under the Govt. of India, Ministry of Surface Transport. The analysis of the survey data was carried out by WS&RS Dte., CWC in association with National Informatics Centre, New Delhi. The gross storage capacity in 1994 reduced to 763.51 Million m^3 indicating -14.79 Million m^3 (negative value) of silt deposited since last survey conducted in 1990. As the results of this survey did not confirm to the last survey, this survey has not been considered in the present report for making comparison of results of satellite based survey with those of previous hydrographic surveys. IRS- LISS III data for seven dates has been used in the analysis. Table 1 gives the Path and Row index along with date of pass of satellite.

Table – 1: Date of pass for satellite data

Satellite	Path	Row	Quadrant	Date of pass
IRS-1D LISS III	98	54	Full Scene	28-Sept.-2001
IRS-1C LISS III	98	54	Full Scene	26-Nov.-2001
IRS-1C LISS III	98	54	Full Scene	15-Jan-2002
IRS-1C LISS III	98	54	Full Scene	06-Mar-2002
IRS-1D LISS III	98	54	Full Scene	20-May-2002
IRS-1C LISS III	98	54	Full Scene	19-June-2002
IRS-1C LISS III	98	54	Full Scene	16-July-2002

Field Data

The following field data has been obtained from project authorities and the earlier sedimentation report:

- Original capacity data
- Reservoir level on date of pass of satellite data.
- Stage-capacity data corresponding to previous hydrographic surveys.

Numerous methods are available for enhancing spectral information content of satellite data. The Tasseled cap transform compresses the total information into three bands: greenness, brightness and wetness. Besides expressing a large image variability within three bands, tasseled cap bands could be directly related to physical characteristics of a scene. Brightness is a weighted sum of all bands defined in the direction of the principal variation in soil reflectance. Greenness is orthogonal to brightness a contrast between the near-infrared and visible bands and is strongly related to the amount of green vegetation in the scene. Wetness relates to canopy and soil moisture. The coefficients to convert the data into brightness, greenness and wetness are not available for IRS LISSIII. Therefore the coefficients available for IRS LISSII and Landsat TM have been applied to the LISSIII data. These three indexes have been calculated using two sensor coefficients for the corresponding wavelength regions. It was found that the results obtained using coefficients of Landsat TM are better. For the Landsat TM, the coefficients for brightness, greenness and wetness functions are (ERDAS Field Guide, 1999):

TM Band	1	2	3	4	5	6
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
Wetness	0.1509	0.1793	0.3299	0.3406	0.306	-0.4572

In this study, the above coefficients were used for IRS LISSIII data for the corresponding wavelength regions. After applying Tassessled cap transformation to an image, three layers are obtained which represent greenness, brightness and wetness, respectively. Then using thresholding technique, the pixels pertaining to water have been identified.

The reservoir elevations at the time of satellite pass were obtained from CWC, New Delhi. The revised areas and the corresponding elevations are presented in Table – 2 for the year 2001-2002.

Table 2 : Reservoir elevation & revised area on the dates of satellite pass

Date of pass	Reservoir Elevation (m)	Number of water pixels	Water spread area estimated using remote sensing (M m^2)
28/09/2001	308.46	203715	117.3
26/11/2001	307.30	187920	108.20
15/01/2002	304.40	128412	73.97
06/03/2002	303.90	123372	71.06
20/05/2002	302.80	109431	63.03
19/06/2002	300.30	73800	42.51
16/07/2002	298.6	45557	26.24

The reservoir capacity between two consecutive reservoir elevations is computed using the trapezoidal formula.

Calculation of sediment deposition in Matatila reservoir is presented in Table 3 after calculating the total water spread area in reservoir.

Table-3: Calculation of Sediment Deposition in Reservoir Using Remote Sensing for the year 2001-2002

Date of satellite pass	Reservoir water level in meters	Surface area using remote sensing	Capacity using remote sensing (Mm^3)	Cumulative Capacity using Hydrographic survey 1962 (Mm^3)	Cumulative Capacity using remote sensing (Mm^3)
28/09/2001	308.46	117.3	130.46	985.71	693.09
26/11/2001	307.30	108.20	262.62	859.21	562.28
15/01/2002	304.40	73.97	31.18	574.94	299.67
06/03/2002	303.90	71.06	77.05	536.91	268.49
20/05/2002	302.80	63.03	134.23	434.18	191.43
19/06/2002	300.30	42.51	57.20	281.42	57.20
16/07/2002	298.6	26.24			

The results show that the volume of sediment deposition during 1962 to 2001-2002 (39 years) in-between the maximum and minimum observed levels (308.46 m and 298.60 m) is $292.63*10^6 m^3$. If the uniform rate of sedimentation is assumed, then as per the 2001-2002 analysis, the sedimentation rate in the zone (308.46 m and 298.60 m) is $7.51 * 10^6 m^3$ per year. Besides the hydrographic surveys of this reservoir carried out by Irrigation Research Institute (IRI) Roorkee, India, a study using remote sensing in the year 1998-99 was carried out by CWC, New Delhi. As per the hydrographic survey between 1962 to 1990 sediment deposition during 28 years comes out to be 236.99, which gives sedimentation rate of $8.46 * 10^6 m^3$ per year. As per CWC study in the year 1998-99, the sediment deposition between 1962 to 1998-99 (36 years) comes out to be $283.38 * 10^6 m^3$, which gives sedimentation rate of $7.87 * 10^6 m^3$ per year. These results are presented in the following table 4. A plot of the capacities computed using hydrographic survey and remote-sensing techniques is shown in Figure 2.

Table 4: Silting rate in Matatila reservoir

Year of impoundment	1962
FRL (m)	308.46
MDDL (m)	295.66
Gross capacity in 1962 (Mm^3)	985.71
Gross capacity in 1998-99 (CWC) (Mm^3)	702.33
Gross capacity in 2001-02 (NIH) (Mm^3)	693.33
Silting rate (CWC) (m^3/sq.km./year)	369.64
Silting rate (NIH) (m^3/sq.km./year)	356.00

Thus the results of hydrographic survey and remote sensing techniques are in close agreement.

CONCLUSIONS AND LIMITATIONS

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

1. Satellite based method for estimating sedimentation is much easier to adopt since little fieldwork is required. However because this is a new technology and there can be some errors in interpretation, the accuracy can be doubted. Using this method initially for reservoir where rigorous hydrographic surveys are done will bring out the accuracy and build confidence.
2. 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.
3. Capacity estimation by Remote Sensing Technique at regular time interval can give important parameters like annual rate of sedimentation and sediment deposition pattern in the reservoir area and provide new Elevation-Area-Capacity curve for optimal operation of the reservoir.

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

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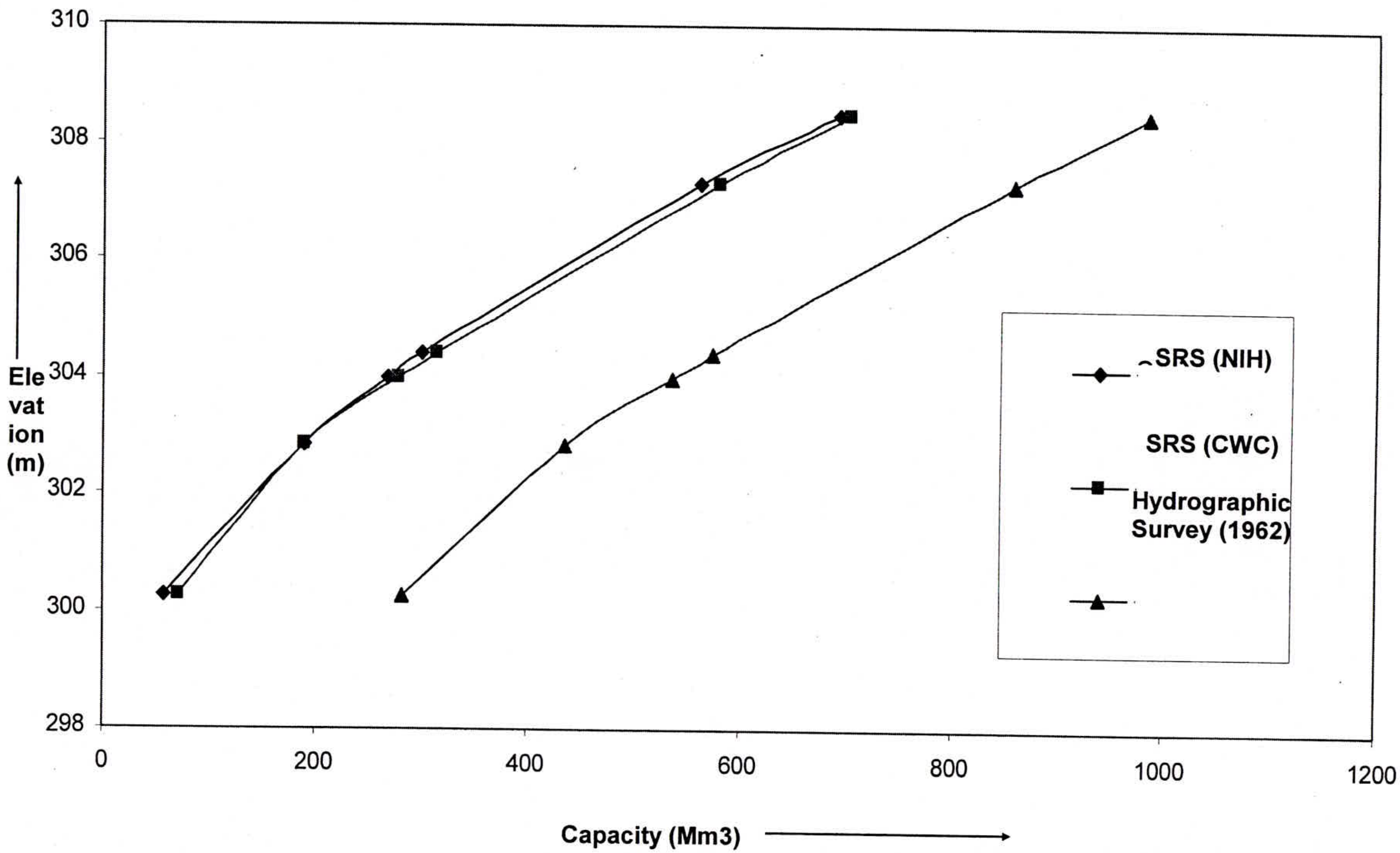

Figure 2: Elevation capacity curves