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Assessment of reservoir sedimentation using remote sensing

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Abstract Efficient management of a reservoir calls for periodic assessment of its capacity. Hydrographic surveys of reservoirs provide valuable information on the rate and pattern of sedimentation, which is required for formulating measures to control sediment inflow and for optimum reservoir operation. Data from space platforms can play a significant role in reservoir capacity surveys. In the recent past, satellite remote sensing has emerged as an important tool in rapid, frequent and economical reservoir sedimentation assessment. Multi-temporal satellite data help in determining water surface areas for different water levels. Any reduction in the reservoir surface area at a specified water level over a time period is indicative of sediment deposition at and below that level. When integrated over a range of water levels, it permits the loss of storage due to sedimentation to be computed. Remote sensing techniques have been used to assess sedimentation rates in a number of reservoirs and the results are described in the paper.

Key words reservoir; sedimentation; remote sensing; image processing; India

INTRODUCTION

The erosion of soil results in the transfer of large amounts of sediment to watercourses. When this sediment enters a reservoir, the coarser particles begin to deposit in the upper reaches of the reservoir due to a decrease in flow velocity. Subsequently, the finer material is deposited further downstream along the reservoir bed. Sedimentation of a reservoir is a natural process, which is of vital concern to all water resource development projects. The rate and pattern of sediment deposition depends on several factors, including the size and texture of the sediment particles, the characteristics of the reservoir outlets, and the size and shape of the reservoir and its operating schedule. Sediment deposition in reservoirs has several major detrimental effects, including loss of storage capacity, damage or impairment of hydro equipment, bank erosion and instability and upstream aggradation. It also impacts water quality and eutrophication. Sediment deposition may also hamper the operation of outlet structures.

To determine the useful life of a reservoir, it is essential to periodically assess the sedimentation rate. In addition, for effective allocation of storage space and management of water in a reservoir, information on the spatial pattern of sediment deposition in various zones of the reservoir is an essential requirement. The theory of reservoir sedimentation has been discussed in many publications such as Garde (1995), Morris & Fan (1998), and Jain & Singh (2003).

METHODS OF ASSESSING RESERVOIR SEDIMENTATION

The methods used to assess sedimentation in a reservoir can be classified into three groups: the inflow–outflow method, the capacity survey method, and the remote sensing method. In the first method, water and sediment inflow into the reservoir as well as their outflow are measured at all significant points of entry and exit. The difference between the sediment inflow and outflow gives the quantity of sediment deposited during the given period. A reservoir may have a number of tributary channels draining into it and it may not be possible to gauge them all. Outflow from the reservoir can take place through spillway, low-level outlets, and irrigation canals. The same approach can be employed for the penstocks used for hydropower generation. Silt ejectors installed in the power house intakes can remove appreciable quantities of sediment and this aspect should be accounted for.

The capacity survey method, often referred to as sedimentation or hydrographic surveys, is a direct measurement procedure, aimed at assessing the volume and spatial distribution of the sediment deposited in a reservoir through periodic surveys. Conventionally, these surveys are conducted using equipment such as theodolites, plane tables, sextants, range finders, sounding rods, echo sounders and slow moving boats. Recent advances in technology and the use of advanced equipment have considerably reduced the effort involved in such reservoir surveys and associated data analysis. Generally reservoirs are surveyed every 3–10 years; the frequency mainly depending on the sediment accumulation rate. Reservoirs having high accumulation rates are surveyed more often than those with lower rates. The cost of undertaking a survey also plays a critical part in deciding their frequency. Special circumstances may necessitate a change in the established schedule. For example, a reservoir might be surveyed after a major flood that has carried a heavy sediment load into the reservoir. A survey may also be undertaken following the closure of a major dam upstream in the same catchment, since the reduction in the uncontrolled drainage area leads to a reduction in the sediment accumulation rate in the downstream reservoir. The volume of the sediment that has accumulated in a reservoir is computed by subtracting the new capacity from the original capacity for a given reference water surface elevation (usually the FRL). Since this represents the difference between two large numbers, any error, even involving only a few percent, in either of the two numbers will significantly influence the results.

Reservoir surveys have many advantages: they can be less costly than continuous sediment measurement undertaken at several locations; the accuracy of these surveys is usually very high; it is possible to take account of the total sediment load (bed and suspended load) transported by the river; and the time required for a survey can be considerably reduced by the use of advanced equipment. Major limitations are that these surveys do not provide any information regarding the temporal variability of the sediment input and only provide information on the total volume of sediment accumulated since the last survey.

The contour and range methods are the two basic approaches used for reservoir surveys. In some situations, a combination is used. The choice of a method depends on the likely quantity and distribution of sediment as indicated by field inspections, the shape of the reservoir, the purpose of the survey, and the desired accuracy. Advanced equipment based on the latest information technology is currently frequently used in hydrographic surveys. An automatic hydrographic data acquisition system consists of three main components: a positioning system, a depth measuring unit, and a computer system to capture, store and analyse the data. In current surveys, the location of the boat is determined by the GPS and acoustic devices are used for depth measurement.

The conventional techniques for quantifying reservoir sedimentation are cumbersome, costly and time consuming. Furthermore, prediction of sediment deposition profiles using mathematical models requires large amounts of data which are rarely available. As a result the potential for using remote sensing techniques has attracted considerable attention in recent years.

THE REMOTE SENSING METHOD

The basic principle of the remote sensing method is as follows. Due to deposition of sediment, the surface area of a reservoir at a given water level or elevation will progressively reduce. Most reservoirs are subject to annual drawdown and refilling cycles. A series of remote sensing images covering a range of reservoir water levels (over one or more water years) can therefore be obtained. These images are analysed to determine the surface area of the water body at the time of the satellite overpass on different dates. The water surface elevation in the reservoir at that time is obtained from the dam authorities. The incremental reservoir storage capacity between the two levels can be computed by the trapezoidal or prismoidal formula and an elevation–capacity table can be prepared. By comparing this table with a previous table it is possible to compute the capacity lost during the intervening period.

The remote sensing approach has the following advantages:

- Due to its spatial, spectral, and temporal attributes, satellite data can provide synoptic, repetitive and timely information regarding the surface area of a reservoir water body.

- By using digital analysis techniques and GIS in conjunction, the spatial pattern of sediment deposition in a reservoir can be determined.
- The remote sensing approach is highly cost effective, easy to use and requires little time for analysis compared to conventional methods.
- Sedimentation can be easily assessed in reservoirs that are located in areas that are difficult to access.

Some limitations of the remote sensing approach are:

- The amount of sediment deposited below the lowest observed water level cannot be determined through this approach. Thus, it is not possible to estimate the sedimentation rate for the entire reservoir.
- The presence of clouds can pose problems in correctly demarcating the surface area of the reservoir water body and hence the sedimentation rate.
- This technique is not suitable for reservoirs located in narrow steep-sided valleys, where the surface area of the water body exhibits little change over a range of water levels.

Key steps in remote sensing analysis

The key steps involved in the remote sensing method are briefly described below.

Selection of the period of analysis If the sedimentation in a reservoir is to be assessed for a specified period, the corresponding data for that period have to be used. Otherwise, it is generally best to use the data of a period providing a large variation in reservoir water level. If historical records of maximum and minimum water level in each year are available, the water year of maximum variation can be selected for sedimentation analysis. A wet year followed by a dry year is the best period for such study. The remote sensing data series for the same water year or contiguous water years must be selected as far as possible. The availability of the satellite data and its cost are additional factors which may govern the selection of the period of assessment.

Selection of suitable satellite and sensor Multi-spectral data are required to identify water pixels and to differentiate them from the peripheral wetland pixels. It is also desirable to use higher resolution data to obtain accurate results. At the present time, a number of satellites acquire remote sensing data and the spatial resolution varies from about 20 m to 1 m or even less. Hence the choice is usually made based on the frequency of satellite passes, spatial resolution, and cost considerations. Ensuring that good quality cloud free satellite data are employed is essential. During the last two decades, India has launched many satellites, whose on-board sensors have the required resolution. Free data may also be obtained from the internet.

Identification of water pixels The basic output from the analysis of remote sensing data is the surface area of the reservoir water body. Satellite data can be analysed by using visual or digital interpretation techniques. Visual techniques are based on the interpretive capability of the operator/analyst and it is not possible to use the information from different bands after the visual product is generated. Around the periphery of the water body, wetland areas may appear very similar to water pixels and it becomes very difficult for the eye to decide whether a pixel near the periphery represents water or land. Hence, visual interpretation is rarely used at the present time. Using digital interpretation, the information from different bands can be put to the best use and the analysis can be consistent. The noise in the imagery can be removed using special algorithms and information about terrain features hidden by the clouds can be indirectly obtained using a sequence of images. It is also easy to calculate the water body area. For these reasons, digital techniques are considered to be superior and are now universally employed.

The reflectance characteristics for vegetation, soil and water are presented in Fig. 1. In the visible region of the spectrum (0.4–0.7 μm), the transmittance of water is significant and the absorbance and reflectance are low. The absorbance of water rises rapidly in the near-infrared region (NIR) (0.77-0.86 μm), where both the reflectance and transmittance are low. Due to transmission of visible radiation through water, if water depth is shallow, the radiation is reflected by the bottom of the water body, transmitted through water, and detected by the sensor. In such situations, it may not be clear from the visible bands whether there is a thin water layer overlying the ground surface. To resolve this, the image in the NIR band must be inspected. In the NIR band, water apparently acts as a black body absorber and the boundary between the water and other surface features is distinct.

The reflectance from the wetland along the reservoir periphery may be similar to the reflectance from the adjacent shallow water. The reservoir water may be muddy. A pixel at the soil–water interface may represent mixed conditions (part water and part soil). To differentiate water pixels from the adjacent wetland pixels, comparative analysis of the digital numbers in different bands is carried out. The behaviour of the reflectance curves of water and soil is different from the blue band (0.53-0.59 μm) onwards. Beyond the blue band, with an increase in wavelength, water reflectance curves show a downward trend while soil curves show an upward trend. This characteristic can be used to differentiate the water pixels from the peripheral wetland pixels. The variation of soil reflectance with moisture content and the reflectance of water under different conditions are shown in Figs 1 and 2, respectively.

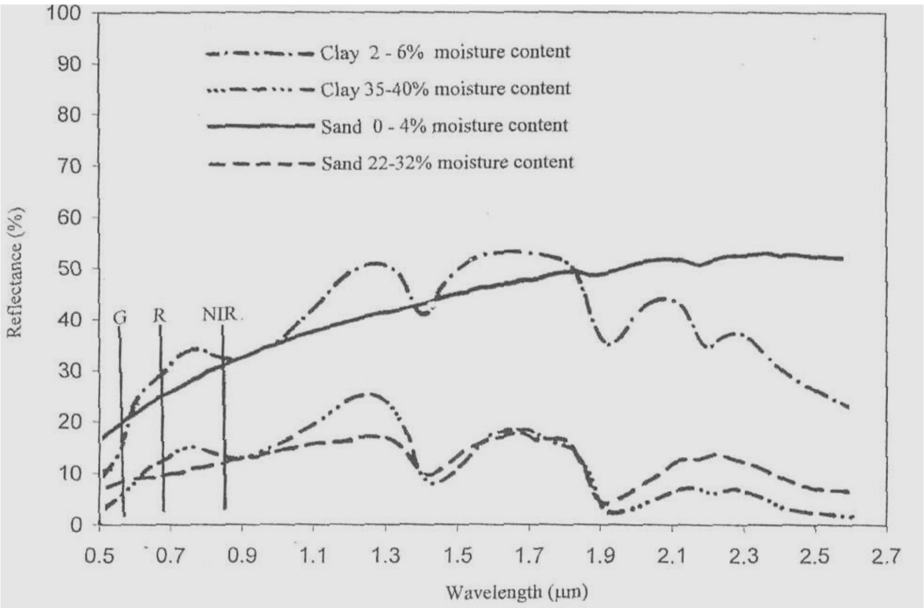

Fig. 1 Spectral reflectance curves for soils.

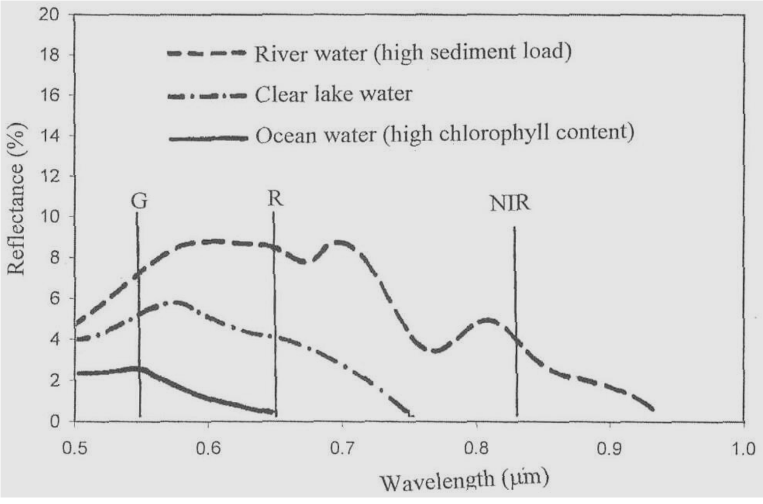

Fig. 2 Spectral reflectance curves for water.

Image analysis Many commercial software packages are available for digital image processing. When using multi-temporal satellite data of the same location, it is necessary to geo-reference the imagery acquired at different times. Geo-referenced imagery can be overlaid and changes in the area of the water body can be detected. Geo-referencing also helps to manipulate the information below clouds and within noisy pixels. An image which is sharp, clear, and cloud- and noise-free is chosen as the base (master). The images for other dates are considered slaves and geo-referenced with the master. Clearly identifiable features, such as crossings of rivers, roads or lineaments, sharp bends in the rivers, bridges, and rock outcrops, are selected as control points. The geo-referencing statistics are examined and the points which have generated large errors are edited/deleted/replaced to obtain satisfactory results. Typically, the final error should be less than the size of a pixel.

Depending on the areal extent and spatial resolution, the file size of each scene may be very large. Since the area of interest is only the reservoir area, the reservoir water body and its surroundings can be extracted from the full scene before proceeding with analysis.

Accounting for cloud effects, noise and tails If the imagery has clouds, their shadows might fall over the reservoir area and its periphery. It is necessary to determine whether the pixels occupied by clouds and shadows correspond to water or not. If clouds and shadows are present over the reservoir area or around the periphery in an image taken during the draw-down cycle, the image for the next cloud-free date is examined. If the area covered by the cloud in a particular image has water at the same location on the next date’s imagery, the pixels below the cloud are classified as water pixels. The reason is that the area occupied by the reservoir water body decreases with time in the draw-down cycle and so the pixels occupied by water on a given date will necessarily have water present on the previous date.

Some pixels may be affected by noise in the data and are interpreted similarly using the images for earlier or subsequent dates. Due to the presence of local depressions around the reservoir periphery, a few water pixels not directly connected with the reservoir might be present near the boundary of the water body. Such pixels that do not form part of the continuous water body should be excluded. Many streams will commonly join the reservoir from different directions around the periphery. Beyond a certain point, these do not form a part of the reservoir. Such tails are suitably removed.

Demarcation of the water body area Many techniques are available to demarcate pixels representing water. Density slicing is used to enhance the information gathered from an individual band. It is undertaken by dividing the range of pixel values in a band into intervals and assigning different colours to each interval. Although most water pixels can be separated out by density slicing, it may fail under certain conditions. The sliced pixels may also include some saturated soil pixels, since the reflectance value for saturated soil is very low in the NIR band. Supervised classification is another approach in which the interpreter knows beforehand what classes of objects (e.g. forest, cropland) are present in the imagery and where (perhaps at many locations) each one is present. A sample site for each class is identified as a training site. All pixels in the image lying outside the training sites are then compared with the class discriminants derived from the training sites, with each being assigned to the class it is closest to – this makes a map of established classes. Although clearly distinguishable water pixels can be easily separated using this technique, it is sometimes difficult to provide accurate training sets for peripheral pixels. Depending on the proportion of the total area covered by water or soil in a mixed pixel, classification of some pixels as totally water and some as totally soil can counterbalance the effect of misclassification to some extent. Another approach is to apply a model that uses multi-spectral data and tests multiple conditions to classify pixels. Most modern packages have a provision to write and execute algorithms.

After the area occupied by the water body has been separated out, the resulting imagery can be compared with the NIR imagery and the standard FCC. Note that the estimation of sedimentation by remote sensing is highly sensitive to determination of the water body area. The use of data from high-resolution sensors helps reduce the error in remote sensing analysis.

Calculation of revised capacity After finalizing the water body areas for all the images, the histograms are analysed and the water pixels in each image are recorded. The water body area at any water level or elevation is obtained by multiplying the number of water pixels by the size of one pixel. The reservoir water level at the time of the satellite overpass is obtained from the reservoir authorities. The reservoir capacity between two consecutive reservoir elevations (ΔV) can be computed using the prismoidal formula:

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

where ΔV 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 ΔH is the difference between elevation 1 and 2. The revised volume can be compared with the original volume in each zone (obtained from the original elevation–capacity table) and the difference between the two represents the capacity loss due to sedimentation. The contours can also be used to prepare a DEM of the area. The DEMs for two different dates can be compared to determine the depth of sediment deposition at various points.

RESULTS AND DISCUSSION

Although sedimentation surveys of reservoirs in India date back to as early as 1870, systematic surveys started in 1958, when the Central Board of Irrigation and Power, New Delhi, undertook a coordinated scheme of reservoir sedimentation assessment by the hydrographic method and entrusted this task to several research stations in the country. Gradually, a number of organizations acquired expertise in hydrographic survey methods and extensive work was done. Murthy (1977) describes the hydrographic survey method followed in three studies. With the launch of Indian Remote Sensing satellites in the 1980s and with imagery becoming easily available, the application of this emerging technique to various disciplines began. It was logical for researchers to explore the application of remote sensing to the assessment of sediment deposition in Indian reservoirs. Some of the studies have been reported by Goel & Jain (1998), Jain *et al.* (1999), and Goel *et al.* (2002).

This contribution presents a summary and analysis of the results obtained from studies of 23 reservoirs undertaken to assess the sedimentation rate using the remote sensing method. The key characteristics of these reservoirs are presented in Table 1. The detailed results of these studies have been documented in a series of reports (Jain *et al.*, 2008).

Attempts were made to compare the results provided by the remote sensing method with those obtained using the hydrographic survey method, but it is difficult to make a precise comparison, because the remote sensing method is unable to determine the deposition below the lowest observed water level during the study period, whereas the hydrographic survey method provides results for the entire reservoir. Nevertheless, comparison of the results for the zone of the reservoir investigated shows that the results of the two techniques are generally within ±4%. Figure 3 shows the elevation *vs* capacity curves for the Ghatprabha reservoir derived using the remote sensing technique and hydrographic survey. It must be recognized that the results of the hydrographic survey might also involve some error.

The storage capacity of the reservoirs studied ranged from 195 to 10 287 Mm^3. The results for all the reservoirs studied have been summarized in Table 2. In this table the assessment zone, the storage capacity, the sedimentation rate and the capacity loss have been listed. Among the reservoirs studied, Matatila has lost nearly 40% of its storage whereas Nagarjuna Sagar has lost about 22 % of its storage. The results presented in Table 2 fail to show any clear regional pattern in the sedimentation rate. Reservoirs in south and central India were found to be losing storage capacity at a high rate. Thus the general assumption that reservoirs located in the Himalayan region experience higher sedimentation rates is incorrect. According to this study, the loss of storage capacity per year varies from 0.95% to 0.027% and, on average reservoirs are losing about 0.5% of their storage capacity per year. This loss is significant in several ways. The economic implications of storage loss are serious and the same is true of the replacement cost. Furthermore, for several reasons, it is becoming increasingly difficult to create new storage space.

Table 1 Key characteristics of the reservoirs studied.

Name of the reservoir	River	State	Catchment area (sq. km)	Remarks
Ghatprabha	Ghatprabha	Karnataka	8829	Data of IRS-1D satellite and LISS-III sensor was used
Gandhisagar	Chambal	Madhya Pradesh	23025	IRS 1D, LISS-III sensors
Vaigai	Vaigai	Tamil Nadu	7031	IRS 1D, LISS-III sensors
Tandula	Tandula	Chhattisgarh	828	IRS 1C/1D, LISS-3 sensors
Linganamakki	Linganamakki	Tamil Nadu	2771	IRS 1D LISS III sensor
Ramganga	Ramganga	Uttarakhand	3134	IRS 1D, LISS-III sensors
Tungbhadra	Tungbhadra	Karnataka	28180	IRS 1D, LISS-III sensors
Barna	Barna	Madhya Pradesh	1176	IRS 1D, LISS-III sensors
Somasila	Pennar	Andhra Pradesh	50492	IRS 1D, LISS-III sensors
Matatilla	Betwa	Uttar Pradesh	20720	IRS 1D, LISS-III sensors
Hirakud	Mahanadi	Orissa	83400	IRS 1D, LISS-III sensors
Tawa	Narmada	Madhya Pradesh	5983	IRS 1D, LISS-III sensors
Lower Manair	Manair	Andhra Pradesh	64645	IRS 1D, LISS-III sensors
Nagarjuna Sagar	Krishna	Andhra Pradesh	215185	IRS 1C, LISS-III sensors
Ravishanker Sagar	Mahanadi	Chhattisgarh	3670	IRS 1D, LISS-III sensors
Lower Bhawani	Cauvery	Tamil Nadu	4200	IRS 1D, LISS-III sensors
Singoor	Manjira	Maharashtra	12096	IRS 1D, LISS-III sensors
Salandi	Salandi	Orissa	1793	IRS 1D, LISS-III sensors
Kolab	Godawari	Orissa	1630	IRS P6, LISS-III sensors
Bhakhra	Satluj	Himachal Pradesh	56980	LISS-III sensor of IRS – 1D satellite
Nizamsagar	Manjira	Maharashtra	21693	IRS 1C, LISS-III sensors

Table 2 Summary of the results of the sedimentation assessments**.**

Reservoir	Period of analysis	Live storage zone (m asl)	Zone of assessment (m asl)	Storage capacity (Mm^3)	Sedimen-tation rate (Mm^3/year)	Sedimen-tation rate (Mm^3/100 sq km/year)	Capacity loss (%)	Capacity loss (%) per year
Nagarjuna Sagar	1967–2002	149.0–179.83	152.28–175.32	10286.98	64.14	0.298	21.82	0.62
Hirakud	1957–2001	179.83–190.00	180.68–185.80	82136.0	21.88	0.263	11.83	0.027
Gandhinagar	1960–2001	381.0 – 400.0	380.57–398.58	7746.0	3.58	0.156	1.0	0.046
Tungabhadra	1981–2002	477.01–497.74	477.45–494.79	3751.0	16.37	0.581	9.16	0.44
Linganamakki	1957–2001	522.73–554.43	532.20–548.78	4417.5	1.70	0.857	1.7	0.038
Tawa	1978–2002	330.9–357.57	338.84–355.12	2311.51	18.74	3.13	19.46	0.81
Ramganga	1974–2001	324.6–365.3	339.05–364.4	2590.72	4.23	1.349	4.57	0.163
Ghatprabha	1974–2001	629.69–662.94	631.1–658.6	1434.14	4.45	3.165	7.75	0.31
Matatila	1962–2002	295.66–308.46	298.6–308.46	985.71	7.51	0.356	38.26	0.76
Somasila	1987–2002	67.05–94.49	83.17–94.39	1158.12	1.60	0.076	2.07	0.138
Lower Manair	1983–2001	270.09–280.42	271.97–276.83	680.65	5.46	0.047	14.45	0.80
Barna	1975–2002	338.1–348.55	338.69–348.55	539.00	3.89	3.309	19.48	0.72
Vaigai	1983–1999	257.56–279.19	264.95–279.03	194.78	0.99	0.142	8.24	0.51
Upper Kolab	1990–2005	844.0–858.0	848.38–855.88	1215.0	0.515	0.316	–	0.042
Ravishanker Sagar	1979–2005	336.21–348.70	337.59–348.72	909.32	1.91	0.520	5.4	0.21
Lower Bhawani	1953–2005	266.0–280.20	266.28–275.47	814	0.76	0.181	5.0	0.093
Singur	1987–2005	510.6–523.60	512.51–523.49	847	8.08	0.668	17.17	0.95
Bhakra	1965–2006	445.62–515.11	484.10–512.27	9373.06	20.07	–	8.77	0.21
Nizamsagar	1930–2006	415.57–428.24	415.80–427.30	841.18	6.13	0.366	55.3	0.73
Tandula	1922–2001	320.45–332.18	320.8–332.18	3122.5	0.28	–	–	–

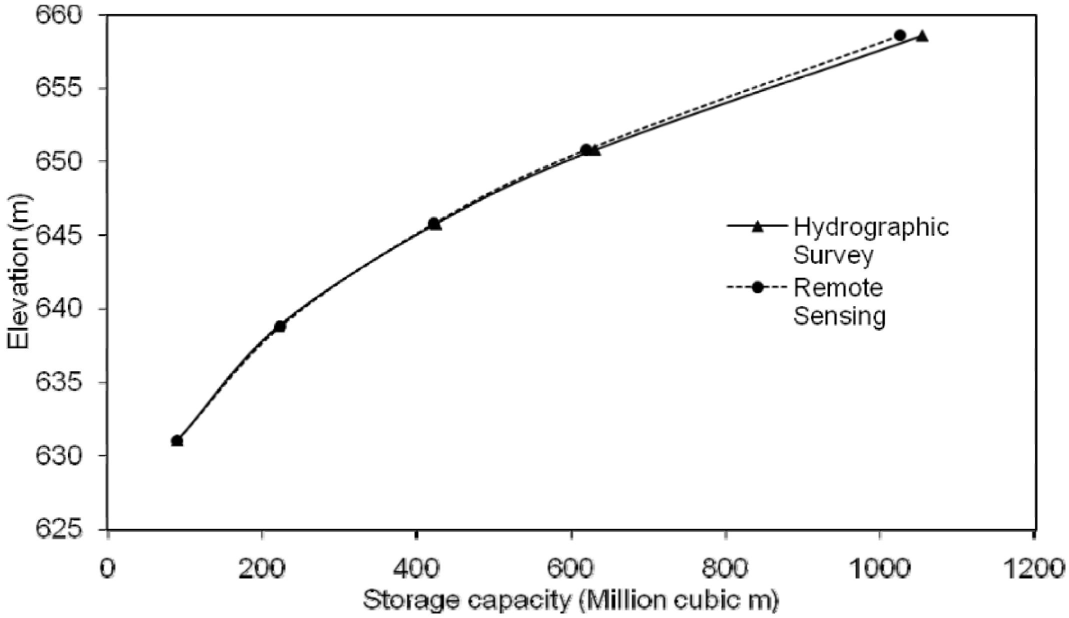

Fig. 3 Elevation capacity curves derived using the remote sensing technique and hydrographic survey for the Ghatprabha reservoir.

CONCLUSIONS

Up-to-date information on sedimentation in a reservoir and the associated loss of storage capacity is essential to plan and implement remedial measures well in advance and to ensure optimum water allocation and management for reservoirs. In view of the cost, time, effectiveness, and the reduction in effort required in comparison to the use of hydrographic surveys, the remote sensing technique has proved to be a useful tool in the assessment of the changing storage capacities of reservoirs. Multi-date satellite data directly provide the elevation contours in the form of water body areas. The major limitation of the remote sensing technique is that the change in capacity in the portion of the reservoir below the lowest observed level and above the highest observed level cannot be determined. This paper presents summary results of sedimentation assessments for 23 reservoirs, based on remote sensing techniques. The annual reduction in storage capacity per year was found to range between 0.95% and 0.027%. The results failed to show any clear regional pattern in the sedimentation rate.

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