Digital Image Analysis Techniques to Estimate Waterspread for Capacity Evaluations of Reservoirs

Abstract

The reduction of storage capacity of a reservoir between two elevation contours over a period of some years would be indicated by the reduction in contour areas at these elevation levels. The waterspreads, which are contour areas at different reservoir operating levels, were estimated for the Bhadra and Malaprabha reservoirs in the upper Krishna river basin using Landsat TM and IRS LISS II digital data, respectively. This paper discusses the digital image analysis strategy adopted for estimation of waterspreads and evaluation of the storage capacity of reservoirs. The possible error component of satellite derived waterspreads due to land-water mixed pixels is analyzed and discussed. For a given reservoir waterspread, the shape factor of the reservoir and the ground resolution of the satellite data have a direct influence on the magnitude of the error component.

Introduction

Periodic deposition of sediments discharged by streams into a reservoir often reduces storage capacity. Information regarding the rate of sedimentation is vital for defining appropriate measures for controlling sediment inflow and for managing the available storage in a reservoir. The rate of sedimentation can be determined by conducting repeated surveys at suitable time intervals. This will enable the periodic evaluation of reservoir capacity. Capacity surveys of reservoirs can be carried out using conventional methods such as hydrographic surveys and ground surveys. However, these surveys are more expensive and time consuming and involve more manpower than do satellite based surveys.

The inputs derived from satellite data for capacity evaluation of reservoirs are the waterspread data at different operating levels of the reservoirs. The ability to map and estimate waterspread from satellite data is well understood, and different techniques such as visual interpretation of satellite imagery, density slicing, and classification of water bodies have been employed for the delineation of a water body (Work and Gilmer, 1976; Thiruvengadachari *et al.*, 1980; Thiruvengadachari and Manavalan, 1983). Hanumantha Rao *et al.* (1985) adopted visual interpretation of enlarged Landsat MSS images to estimate the waterspreads at eight different levels of the Sriramsagar Reservoir. Suvit Vibulsreth *et al.* (1988) employed digital techniques in which density slicing of Landsat MSS near-IR (0.8 to 1.1 μm) data were used to extract the waterspreads of the Ubolratana Reservoir on five different dates.

White (1978) examined a variety of measuring techniques for determining reservoir surface areas extracted from Landsat MSS near-IR imagery of different scales and compared their accuracy with field data. He concluded that none of the measuring techniques used was able to measure the reservoir waterspreads with consistent accuracy and no reason was attributed. Managond *et al.* (1985) employed digital classification techniques to estimate the waterspread of the Malaprabha Reservoir on 02 March 1973 using Landsat MSS data and reported a discrepancy of +8.29 percent from the actual waterspread. This discrepancy was attributed to the probable misclassification of boundary pixels.

Analysis of multidate satellite data can directly provide elevation contours in the form of waterspread boundaries which, when compared with those at different stages of the sediment deposition process, would delineate the changes in waterspread (at different elevation levels) and sediment deposition pattern. The reduction in waterspread at different elevation levels can be the input to the following CONE formula used for computing the sediment volume:

$$V_s = 1/3\,(A_1 + A_2 + \sqrt{A_1 * A_2})h$$

where V_s is the sediment volume,
A_1 is the reduction in waterspread at reservoir level 1,
A_2 is the reduction in waterspread at reservoir level 2, and
h is the difference in height between levels 1 and 2.

Attempts have been made by Hanumantha Rao *et al.* (1985), Suvit Vibulsresth *et al.* (1988), and others to use satellite derived waterspreads for the capacity evaluation of reservoirs. However, no quantitative analysis has been made to assess the reliability of such waterspread estimates.

This paper discusses the digital image analysis techniques to be adopted for extraction of waterspread contours and estimation of waterspreads. The error analysis of waterspread estimates with regard to land-water mixed pixels is also addressed.

Methodology

The Bhadra Reservoir on the Bhadra River and the Malaprabha Reservoir on the Malaprabha River, both of which form part of the Krishna River system, were studied (Figure 1). The Bhadra Reservoir project was completed in 1964 and the Malaprabha Reservoir project in 1972. The waterspread

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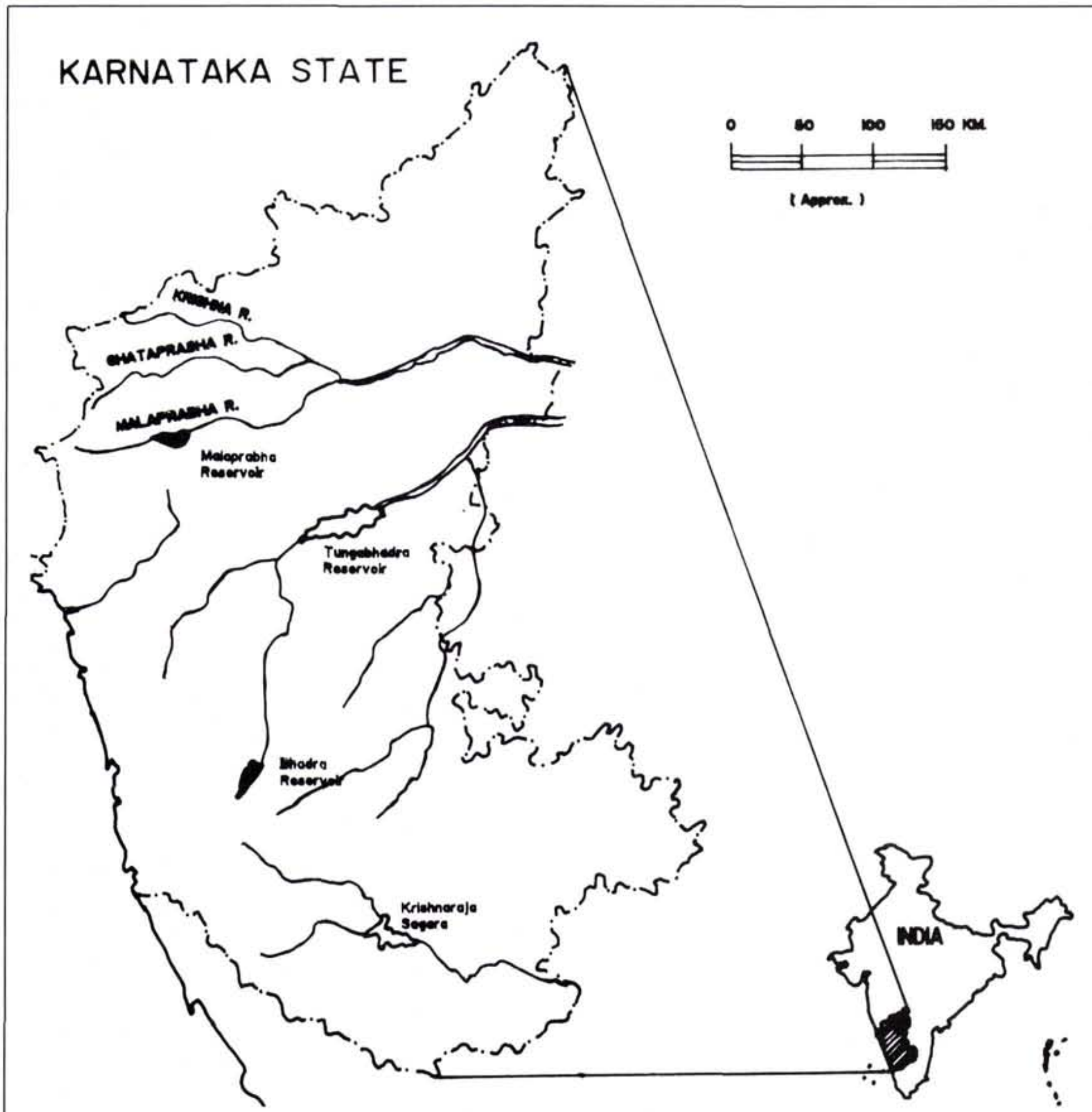

Figure 1. Location of the Bhadra and Malaprabha reservoirs.

at Full Reservoir Level (FRL) of these reservoirs is 117.30 km² and 128.08 km², respectively. The total catchment area of the Bhadra Reservoir is 1968.40 km² and is mostly under forest cover. A siltation rate of 10.78 million cubic feet (0.30 million cubic metres) per year is estimated using the Inglis formula*. The total catchment area of the Malaprabha Reservoir is 2150.40 km². Of this, approximately 55 percent is cultivated, 13 percent is covered by forest, and the remaining is covered by grazing lands and other land covers. A siltation rate of 27.64 million cubic feet (0.78 million cubic meters) per year is estimated using the Inglis formula.

Under the Application Validation Program (AVP) of the Regional Remote Sensing Service Centres-National Natural Resources Management System (RRSSC-NNRMS), we examined the applicability of satellite digital data for extraction of waterspreads at different levels of the Bhadra Reservoir for updating the elevation contours. For this purpose, we acquired Landsat TM data in Computer Compatible Tapes (CCTs) for three dates: 25 March 1986, 12 May 1986, and 01 September 1986. While the reservoir as seen from the data of 25 March 1986 and 12 May 1986 was free from cloud cover, it was covered by thin cloud on 01 September 1986.

The results of the initial study were encouraging; hence, capacity evaluation of the Malaprabha Reservoir was made using IRS LISS-II imagery from five dates: 20 May 1988, 21 October 1988, 26 December 1988, 08 February 1989, and 24 March 1989. The imagery was of good quality and cloud free.

We acquired the standard CCT products, corrected for radiometric and geometric errors, from the National Remote Sensing Agency (NRSA), Hyderabad. We selected the specific satellite data based on a need to provide the representative waterspreads at levels ranging between the minimum draw down level and the full reservoir level of the reservoir and to maintain good quality and cloud free data.

Density slicing in the near-IR band (0.76 to 0.90 μm for

*An empirical formula relating silt yield with catchment area modified for its land-cover and soil characteristics.

the Landsat TM and 0.77 to 0.86 μm for the IRS LISS-II) was performed for all the data except for that of 01 September 1986 covering the Bhadra Reservoir, for which we employed digital classification using multiband data.

Histogram analysis of individual band data revealed that the near-IR band data could provide a distinct grouping of water pixels and quite a sharp transition from water pixels to land pixels. A decision boundary had to be chosen from this transition zone to separate out the water pixels from the land pixels. However, in single band data it would be difficult to chose this significant grey value.

Work and Gilmer (1976), who employed a single band thresholding approach and multiple band approach, observed that the thresholding technique on Landsat MSS band 7 provided rapid and accurate recognition of lakes and large ponds. Further, their technique, which uses the increased information content of multiple spectral bands, provided recognition of a greater number of small ponds not previously identified. This indicated that adoption of a thresholding technique alone on near-IR data would result in under estimation of total open water surface area and that analysis of multiband data would be required to improve accuracy.

Selection of the decision boundary from the transition zone with the near-IR band data can be effectively made by verifying the resulting land-water boundary line on the False Color Composite (FCC) of the near-IR band and two visible bands. By doing this, inclusion of shallow water pixels and high proportionate water pixels usually distributed along the land-water boundary is possible, leading to near accurate estimation of waterspread.

Under field conditions, the land-water transition environment will not be the same along the entire water boundary. The reservoir bank steepness generally will be greater near the damsite while it will be less in the areas where streams join the reservoir. Moreover, the land adjoining the reservoir will be of a different type and its soil moisture conditions will vary. All these will influence the selection of the decision boundary, and this will vary along the perimeter of water bodies depending upon field conditions. Hence, it would be a worthwhile effort if the image covering the reservoir and the adjoining land features is segmented into subimages for the purpose of density slicing, or the land mass is somehow "masked" and removed from the analysis. Once the water pixels are selected out from the non-water pixels, area estimation can be done by counting the total number of pixels and multiplying that total by the ground resolution of the pixel. Thus, the waterspread estimates have to be obtained for all the dates.

To find out the possible error components in such estimates that may have been introduced due to land/water pixels in the way of commission or omission, the following analogy is developed:

Let P be the number of pixels forming along the perimeter of the waterbody, H be the pixel height in metres, and W be the pixel width in metres.

Assume that

(1) the probability of having a mixed land-water pixel *vis-a-vis* a homogenous pixel at the perimeter is 0.5, and
(2) in a mixed land-water pixel the proportion of water area ranges between values tending to zero and one hundred percent.

If all the mixed pixels are considered for area estimation and the proportion of water in all these pixels tends towards zero, then the error due to commission will be

$$\frac{+P \times H \times W}{2 \times 10^6}\ \text{km}^2$$

If all the mixed pixels are not considered and the proportion of water in all those pixels is tending to one hundred percent, then the error due to omission will be

$$\frac{-P \times H \times W}{2 \times 10^6}\ \text{km}^2$$

Thus, if SW is the satellite derived waterspread in km², the actual waterspread can be anywhere between

$$\text{SW} - \frac{P \times H \times W}{2 \times 10^6}\ \text{km}^2 \text{ and } \text{SW} + \frac{P \times H \times W}{2 \times 10^6}\ \text{km}^2$$

It can be noted that, if the satellite derived waterspread is estimated at more than the project figure after adding the error component, the reduction in waterspread is considered to be nil. Comparisons between the satellite derived waterspreads for different reservoir levels and the corresponding waterspreads as per earlier field surveys can be used to determine the reduction in waterspreads at those levels. Any significant reduction of a waterspread at a given water level beyond the upper error limit will be a more dependable determination of the reduction in capacity at that level.

Digital analysis of satellite data was carried out using the VIPS 32 image processing system running on a VAX 11/780. The image covering the reservoir was segmented into subimages of 512 by 512 pixels to match the resolution of the display monitor. The Bhadra Reservoir area on all the three dates was covered by two such image windows. The Malaprabha Reservoir area was covered by one to four image windows, depending upon the extent of waterspread. Each subimage was analyzed independently on the PERICOLOR work station. The generalized procedure, indicating the methodology for capacity evaluation of large reservoirs using digital image analysis techniques, is shown in Figure 2.

Results and Discussion

The water-land transition zones of the histograms of near-IR band data were carefully analyzed to select the decision boundaries by obtaining the best fitting water boundary line on an FCC of bands 2, 3, and 4. Figure 3 shows the transition zones in the histograms of the sub-images of the Bhadra Reservoir on 25 March 1986 and 12 May 1986. The image cut-off digital numbers (decision boundaries) obtained for different sub-images are given in Table 1. The waterspread contours of the Malaprabha Reservoir as a result of the above cut-off digital numbers are shown in Figure 4.

The total number of water pixels (W_p) obtained for each date was converted into geographical area by multiplying it with the ground resolution of each pixel (30 m by 30 m for Landsat TM; 36.25 m by 36.25 m for IRS LISS-II). The results are presented in Table 2. The satellite derived waterspreads of the Bhadra Reservoir for the three dates are shown in Figure 5.

Error analysis of all the waterspread estimates except that for the one obtained using the image classification technique was done. The number of land-water boundary pixels (B_p) for each date data was derived from the waterspread contour obtained in the form of an image on the display monitor. In Table 3, the computed error components of satellite derived waterspreads are presented along with the waterspreads as per the earlier field survey.

The magnitude of the error component in the satellite derived waterspread estimation is bound to increase with the increase in the number of boundary pixels and decrease with the increase in pure water pixels. The relationship between the ratio of mixed pixels to pure water pixels and the magni-

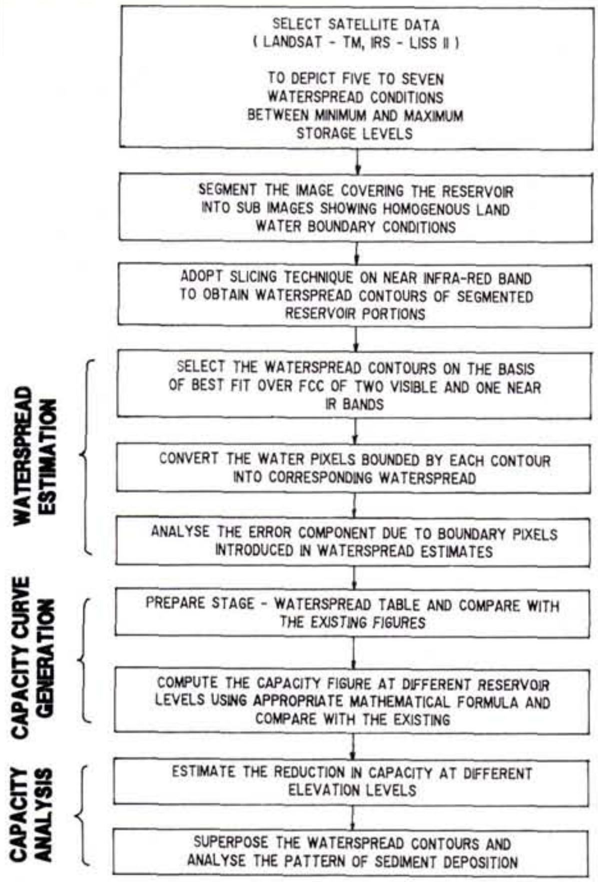

Figure 2. Step-by-step procedure adopted for capacity evaluation of reservoirs (the last step of the "Sediment Deposition Pattern Analysis" was not performed in this study).

tude of the error component is studied. Crapper (1984) used the "shape factor" while developing a formula for determining the number of boundary cells and the standardized error of area estimates for a regionalized map. The "shape factor" (K) is dimensionless and is defined to be

$$K = \frac{L}{2\sqrt{\pi A}}$$

where L is the length of the perimeter and A is the area of the polygon. In the present study, a simplified factor for determining the shape of the reservoir is proposed and is expressed as

$$S_f = \frac{B_p}{2\sqrt{\pi W_p}}$$

where S_f is the reservoir "shape factor," B_p is the number of boundary pixels, and W_p is the number of water pixels. Table 4 compares the reservoir "shape factor" and the magnitude of the error component.

The results indicated that,

- for the given waterspread, the Bhadra Reservoir will have a longer perimeter than the Malaprabha Reservoir and, hence, the error component will be greater for the former; and
- the "shape factors" of the Bhadra and Malaprabha Reservoirs

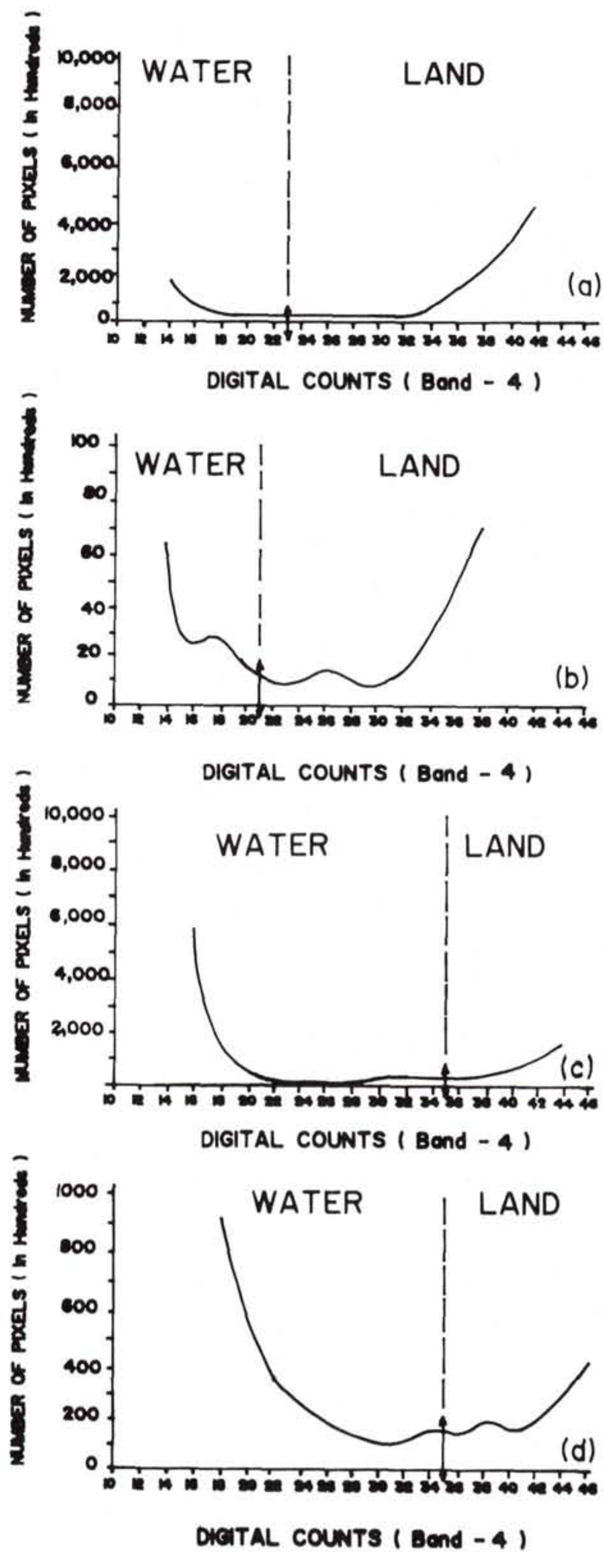

Figure 3. Water-land transition zones as observed on the histograms of subimages of the Bhadra Reservoir. (a) Transition zone in histogram of image window 1 of 25 March 1986. (b) Transition zone in histogram of image window 2 of 25 March 1986. (c) Transition zone in histogram of image window 1 of 12 May 1986. (d) Transition zone in histogram of image window 2 of 12 May 1986.

Table 1 Cut-Off Digital Numbers Chosen for Different Image Windows to Select the Water Pixels from Others.

S1. No.	Reservoir	Satellite data	Date	Cut-off digital numbers in band 4 of image window 1	2	3	4
01.	Bhadra	LANDSAT-TM	25 Mar 86	23	21	–	–
02.	Bhadra	LANDSAT-TM	12 May 86	35	35	–	–
03.	Malaprabha	IRS LISS-II	20 May 88	31	–	–	–
04.	Malaprabha	IRS LISS-II	21 Oct 88	25	25	25	24
05.	Malaprabha	IRS LISS-II	26 Dec 89	10	17	13	17
06.	Malaprabha	IRS LISS-II	08 Feb 89	18	19	16	–
07.	Malaprabha	IRS LISS-II	24 Mar 89	30	28	26	–

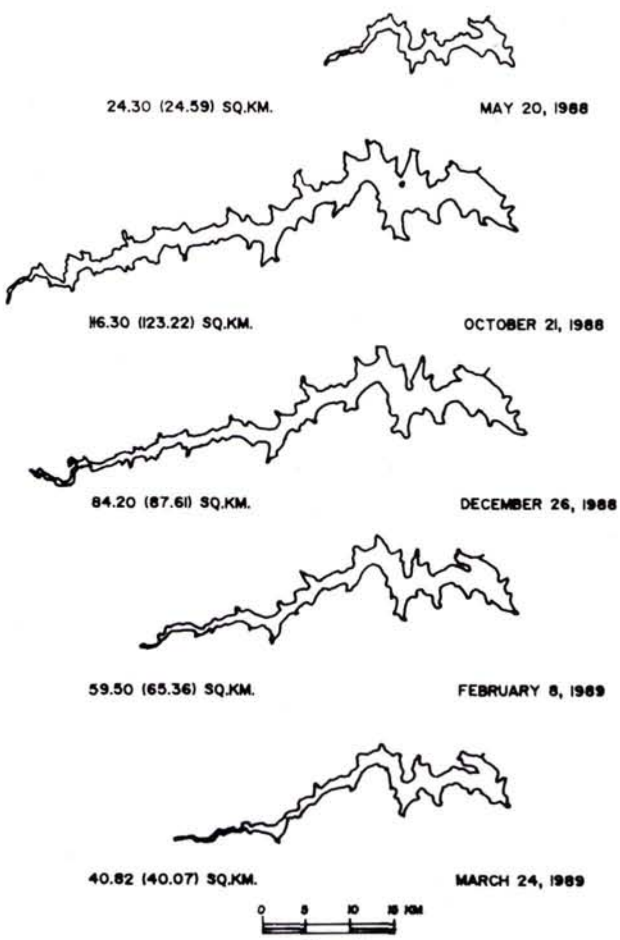

Figure 4. Waterspread contours of the Malaprabha Reservoir derived from the near-IR band data of IRS LISS II on the basis of a best fitting line on FCC of bands 2, 3, and 4. Satellite derived waterspread areas are given as against the figures (in paranthesis) derived from the existing *stage-capacity curve*.

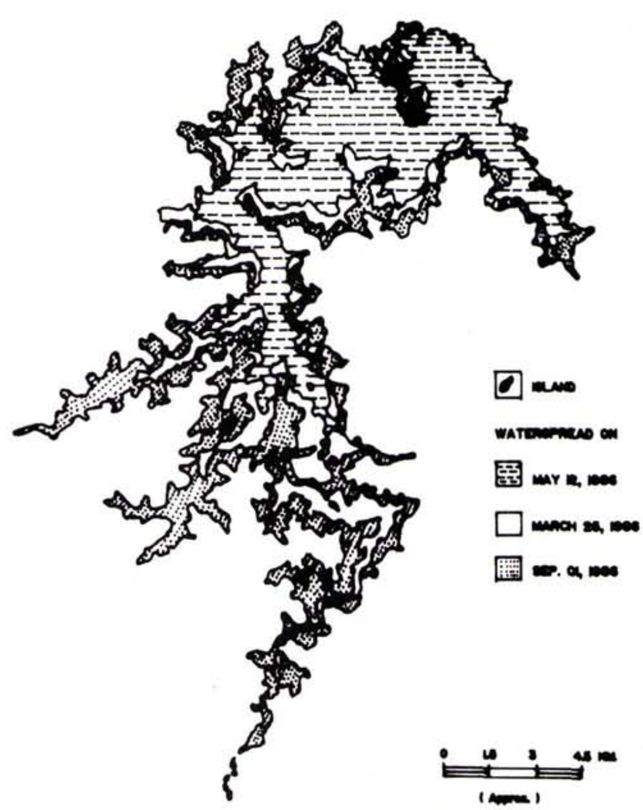

Figure 5. Multilevel waterspreads of the Bhadra Reservoir superposed one over the other.

at different waterspreads are on the order of 8.0 to 9.1 and 3.4 to 4.89, respectively.

When capacity reduction of a reservoir due to sedimentation is to be estimated using the satellite derived waterspreads, it is always better to assess and specify the possible error limit. Otherwise, the discrepancy between the actual waterspread and the satellite derived waterspread will lead to a misleading conclusion regarding the rate of sedimentation, especially when there is only marginal deposition of sediments.

The reduction in capacity between contours at levels 638.50m and 644.29m for the Bhadra Reservoir and between contours at levels 620.15m and 632.98m for the Malaprabha Reservoir is computed and presented in Table 5.

For the Bhadra Reservoir, the reduction in capacity between contours at 638.50 m and 644.29m is estimated to be anywhere between 0.83 percent and 12.3 percent in the time space of 22 years (1964-1986). For the Malaprabha Reservoir, the reduction in capacity between contours at 620.15m and 632.98m is estimated to be anywhere between 0.5 percent and 7.8 percent in the time span of 17 years (1972-1989).

TABLE 2 COMPUTED WATERSPREADS OF THE RESERVOIRS FROM DIFFERENT DATES OF THE SATELLITE DATA

Sl. No. Reservoir	Date	Digital Technique	Total No. of Water Pixels (Wp)	Waterspread (km^2)
01. Bhadra	25 Mar 86	Density slicing of Landsat TM band 4 data	68124	61.31
02. Bhadra	12 May 86	– " –	47087	42.38
03. Bhadra	01 Sep 86	Supervised classification on Landsat TM bands 2, 3, and 4	113890	102.50
04. Malaprabha	20 May 88	Density slicing of IRS LISS II band 4 data	18488	24.30
05. Malaprabha	21 Oct 88	– " –	88505	116.30
06. Malaprabha	26 Dec 88	– " –	64070	84.20
07. Malaprabha	08 Feb 89	– " –	45283	59.50
08. Malaprabha	24 Mar 89	– " –	31064	40.82

TABLE 3. ESTIMATED ERROR COMPONENTS OF COMPUTED WATERSHEDS

Sl. No.	Reservoir	Water level above MSL(m)	Waterspread (Sq.km) Project Figure	Satellite Derived	No. of boundary pixels (Bp)	Error Component (km^2)
01.	Bhadra	638.50	45.13	42.38	6210	± 2.79
02.	Bhadra	644.29	65.46	61.31	8494	± 3.82
03.	Bhadra	655.82	110.21	102.50	—	—
04.	Malaprabha	620.15	24.59	24.30	1641	± 1.08
05.	Malaprabha	623.54	40.07	40.82	2954	± 1.94
06.	Malaprabha	626.53	65.36	59.50	3545	± 2.33
07.	Malaprabha	629.56	87.61	83.20	4268	± 2.80
08.	Malaprabha	632.98	123.20	116.30	5154	± 3.39

TABLE 4. RELATIONSHIP BETWEEN THE RESERVOIR SHAPE FACTORS AND THE ERROR COMPONENTS

Sl. No.	Reservoir	Date	No. of boundary pixels (Bp)	No. of Water pixels (Wp)	Shape facator (Sf)	Error Component (Sq.km)
01.	Bhadra	12 May 86	6210	47087	8.07	± 2.79
02.	Bhadra	25 Mar 86	8494	68124	9.18	± 3.82
03.	Malaprabha	20 May 89	1641	18488	3.40	± 1.08
04.	Malaprabha	24 Mar 89	2954	31064	4.73	± 1.94
05.	Malaprabha	08 Feb 89	3545	45283	4.70	± 2.33
06.	Malaprabha	26 Dec 88	4268	64070	4.76	± 2.80
07.	Malaprabha	21 Oct 88	5154	88505	4.89	± 3.39

TABLE 5. SATELLITE DERIVED CAPACITY REDUCTION BETWEEN CONTOURS

Sl. No.	Reservoir	Water level above MSL(m)	Reduction in waterspread as per satellite data (Sq. km.)	Reduction in Capacity between contours as per satellite data (Mcum)	Reservoir Capacity between contours as per project figs. (Mcum)
01.	Bhadra	638.50	Nil to 6.57	—	—
02.	Bhadra	644.29	1.36 to 6.94	2.625 to 39.107	316.954
			Total:	2.625 to 39.107	316.954
03.	Malaprabha	620.15	Nil to 1.37	—	—
04.	Malaprabha	623.54	Nil to 1.19	Nil to 4.336	109.580
05.	Malaprabha	626.53	3.53 to 8.19	5.391 to 12.440	153.922
06.	Malaprabha	629.56	0.61 to 6.21	5.663 to 21.747	231.117
07.	Malaprabha	632.98	3.53 to 10.31	6.392 to 27.955	357.625
			Total:	17.446 to 66.498	852.244

Conclusions

Thresholding of near-IR band data proves to be a simple and useful technique for the area estimation of reservoir waterspread. The threshold digital value or decision boundary, if chosen on the basis of the best fitting waterspread boundary on the FCC, will result in improved estimation of waterspread. The reservoir shape factor and the ground resolution of the satellite data have a significant influence on the magnitude of the error component of a waterspread estimation. More accurate estimates of waterspreads and, thus, reliable information on reduction in capacity due to sedimentation is possible if satellite data with higher spatial resolution are used for the reservoirs with "shape factors" at their minimum.

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