WORKSHOP

ON

RESERVOIR SEDIMENTATION ASSESSMENT USING REMOTE SENSING DATA

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Module 2

Assessment of Sediment Deposition Pattern in a Reservoir Using Satellite Data

BY

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ABSTRACT

A reservoir is an integral component of a water resources system. Periodic evaluation of sediment deposition pattern and the assessment of available storage capacity of reservoirs is an important aspect of water resources management. The conventional techniques of quantification of sediments 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 input data and the results are still not encouraging.

Remote sensing technique, through its spatial, spectral and temporal attributes, can provide synoptic and repetitive information regarding the water spread area of a reservoir. At an elevation, the water spread area of reservoir keeps on decreasing with sedimentation. By using the remote sensing data and the geographic information system in conjunction, the temporal change in water spread area can be analysed to evaluate the sediment deposition pattern in the reservoir. A case study, related to the assessment of sediment deposition in Ukai reservoir, Gujarat state, India, is presented. The data of IRS-1B LISS-II sensor is used and the analysis is performed using the ERDAS/IMAGINE software.

INTRODUCTION

Soil is eroded due to rainfall and winds, resulting in tremendous sediment movement into water courses by flood and storm waters. A great amount of sediment is annually carried by the rivers down to the reservoirs, lakes, estuaries, bays, and oceans. Analysis of sedimentation survey in respect of 43 reservoirs in India, indicate that the sedimentation rate varies between 0.3 to 27.85 ha-m/100 sq km/year [11]. Continued deposition of sediments in course of time leads to reduction in the storage capacity of reservoirs and conveyance of rivers and hence in the anticipated benefits.

More than 3000 major and medium river valley projects have already 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 that threaten the longevity of such projects is the accumulation of sediments in the reservoirs. In order to determine the useful life of a reservoir, it is essential to periodically assess the sedimentation rate in a reservoir. Further, periodic investigations into the amount of sediments entered into the reservoir and their deposition pattern are also necessary for maintaining operational efficiency of reservoirs. With the correct knowledge of sedimentation process going on in a reservoir, remedial measures can be undertaken well in advance and reservoir operation schedules can be planned for optimum use of water.

In India, the agencies involved in sedimentation studies are the Central Water Commission, CWPRS, Soil and Water Conservation Division of the Ministry of Agriculture, River Valley Authorities and various state government departments. The reservoir surveys in India date back to 1870. In the post independence period after 1947, a large number of reservoirs have been surveyed. The mode of surveys is mostly by hydrographic techniques. In a few instances, inflow-outflow method is also used to quantify the sedimentation in reservoirs. These methods are laborious, time consuming, and costly and have their own limitations. Two state of art reports on this topic have been prepared by Garde [5] and Varshney [12]. With the introduction of remote sensing techniques in the recent past, it has become very cheap and convenient to quantify the amount of sedimentation in a reservoir and to assess its deposition pattern [1]. The basic data interpreted from the remote sensing technique is the water spread area of the reservoir on different dates of satellite pass.

In the early stages of development of remote sensing technology, the reservoir waterspread areas were delineated using the visual interpretation techniques [2]. However, along the periphery of the reservoir, the depth of water generally remains shallow and the difference in reflectance from wet soil and shallow water is not very apparent. So, using this technique, the correct demarcation of water pixels along the periphery was very difficult. Due to the increase in the computational capabilities with time, digital techniques became more popular. Density slicing of the infrared band was mostly employed for the water spread area calculation [3, 4, 8, 9, 10]. Again, this technique is based on the subjective judgement of the analyst and was prone to error. Recently, researchers are trying to classify the water pixels on the basis of spectral signature characteristics of water thereby avoiding the necessity of selecting arbitrary limits.

GENERAL METHODOLOGY OF SEDIMENTATION ASSESSMENT

In India, more than 80% of the annual rainfall occurs during four monsoon months from June to September. The water level in a reservoir attains the higher elevation at the end of monsoon season (around end of September). It then gradually depletes and attains the lower level before the onset of next monsoon (around the end of May). With the deposition of sediments in the reservoir, the water spread area at the corresponding elevation decreases. Using the satellite data, the water spread area of the reservoir at the time of satellite pass can be determined. Revised contour area, after the process of sedimentation, can be taken as the continuous water spread area of the reservoir at the elevation of water surface. Water levels in the reservoir corresponding to the time of satellite pass can be obtained from the dam authorities. In this way, revised contour areas can be calculated and the revised elevation-area curve can be prepared. The original elevation-area curve can be obtained from the original capacity surveys, which are carried out before the construction of the dam.

The reduction in reservoir capacity between consecutive contour levels can be computed using the prismoidal formula. A few factors which need to be considered for such analysis are discussed below:

a) Period of Analysis

Though any water year can be selected for the analysis, it is best to carry out the analysis of such a period when there is maximum variation in the reservoir water level. If the historical records of maximum and minimum reservoir level in each year are available, the water year of maximum variation is a better selection. A wet year followed by a dry year is the best period for such analysis. The remote sensing data must be selected judiciously so as to cover maximum elevation range of the reservoir. The availability of satellite data, its cost and the relative change in reservoir elevation are the additional factors which govern the selection of period of analysis.

b) Suitable Satellite and Sensor

A number of satellites are available and the most common among them are listed below along with their sensors and spatial resolution:

a) IRS - 1A/ IRS - 1B [LISS-I (72.5 m) & LISS-II (36.25 m)]
b) IRS - 1C [PAN (5.8 m) & LISS-III (23.5 m)]
c) LANDSAT [MSS (80 m) & TM (30 m)]
d) SPOT [PAN (10 m) & spectral (20 m)]

Multi-spectral information is required for the differentiation of water pixels from other land uses. For the period 1988 to 1995, the data of IRS-1A/1B can be used while after the year 1995, the data of IRS-1C satellite can be utilised. For the IRS-1C satellite, the spectral information of LISS-III sensor can be merged with the data of PAN sensor to find the water spread area calculation at the resolution of 5.8 m. This can greatly enhance the accuracy of determination of water spread area and the subsequent contour line.

c) Identification of Water Pixels

The basic output from the remote sensing data analysis is the water spread area of the reservoir. The water pixels in the main body of the reservoir are quite distinct and clear in the FCC and the near-IR imagery. However, along the periphery of water spread, the wet land appears very similar to the shallow water pixels. Visual techniques of water spread delineation 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. 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 spread of the reservoir. For these reasons, digital techniques are superior and are gaining recognition now-a-days.

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 shallow water causes the bottom of the water body to reflect appreciably and in such cases, it may not be clear from the visible bands whether the detected surface is above or below the water surface. For resolving this issue, the image in the near-IR portion of the spectrum is inspected. At near-IR 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, 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 digital numbers in different bands is carried out. The signatures of water and soil/vegetation show opposite trends from 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.

d) Estimation of Depth of Sediment Deposition

Once the water spread area is identified in the satellite image, the discontinuous pixels of water (within the islands and in depressions around the periphery) are removed by manual editing. The contour corresponding to the water spread can be obtained by convoluting the water spread image with a high pass filter. Likewise, the contours at different elevations on the different dates of pass can be obtained. With the revised contour information as input, the revised digital elevation model of land surface within the submergence area of the reservoir can be prepared in a GIS system using any method of interpolation. Similarly, the original digital elevation model of the area can be obtained by utilising the original contours of the area in a GIS system. An image showing the difference between the two DEMs can be obtained which gives the grid-wise depth of sediment deposition at any point in the submergence area. If the hydrographic survey report of the reservoir for the corresponding period is available, then a comparison between the calculated and observed sediment deposition pattern in the reservoir can be made.

CASE STUDY OF UKAI RESERVOIR

The results of a case study for Ukai reservoir are summarised here. Ukai is the largest multipurpose project so far completed in Gujarat state. The dam is located across river Tapi in district Surat in Gujarat state. The total catchment area of the Ukai reservoir is 62,225 sq. km. The dam was completed in the year 1972. For this study, the water level variation in each water year was analysed. In the year 1993, maximum level at 104.775 m (343.75 ft) was observed on 5.10.93. The reservoir level fell gradually till the minimum level of 85.033 m (278.98 ft) was observed on 6.7.94. This period was selected for the study and data of IRS-1B satellite and LISS-II sensor were used. Based on the status of remote sensing data availability, eight dates were chosen from November, 1993 to June, 1994 and the data of one date in each month were obtained. These dates are given in Table - 1. The reservoir water spread area was covered in A1 quadrant of Path 30 and Row 53 of the satellite.

The data were processed and analysed using the ERDAS/IMAGINE 8.3.1 software (Goel et al, 1998). Temporal satellite images were geo-referenced. Using the geo-referenced imageries, it was possible to overlay the images of different dates for comparing the temporal change in the water spread area. Geo-referencing was also used to manipulate the information below clouds and noise pixels using the imageries of adjacent dates. A generalised algorithm (values of ratioed images of B4/B2 and B4/B3 less than unity for water pixels) was used for differentiating the water pixels. The resulting water spread was compared with the standard FCC and the near-IR image for all the dates and the results were satisfactory in all cases. The images of water spread, as obtained from the interpretation, were edited to remove the effect of clouds, noise, isolated water pixels, and extension of tail.

a) Interpretation Below the Clouds

Two images had some cloud cover. First, the clouds were exclusively identified in the images by density slicing. The Band 3 information was utilised for the purpose as the clouds are the brightest feature in this range. For interpreting the area within the reservoir below the clouds and shadows, the imagery for the next available cloud free date was examined. If the area covered by the cloud in a particular imagery had water at the same location on the subsequent date's imagery, the pixels below the cloud were classified as water pixels. For the clouds located on the periphery, the trend of water line was demarcated from the previous and past date imageries and the pixels under the clouds or shadows were classified as water by copying the water pixels. The FCC and the imagery of adjacent dates was used while editing.

b) Elimination of Noise

In some imageries, especially November, 1993, there was considerable noise in the data. Most of the noise affected pixels were isolated and it was relatively easy to determine whether the affected pixel represents water or land. Noise pixels were not classified as water by the model. Most of the noise within the water spread was removed by using the subsequent date image. For the rest of the waterspread area not covered in the subsequent image, noise pixels were edited by confirming the status of the pixel from the FCC.

c) Elimination of Isolated Pixels

As the reservoir level falls, small islands appear within the reservoir area. Due to the presence of local depressions within the islands and around the periphery, a few pixels within the depressions appear as water pixels. Since the contour area represents the continuous area, the isolated water pixels within and outside the water spread area were removed from the interpreted image by editing.

d) Elimination of Tail

Main river at the tail end and the numerous small channels that join the reservoir from different directions do not represent the reservoir elevation and these must be excluded from the calculation of the water spread area. For selecting the tail end on different dates, the tail end of the imagery of November, 1993 and June, 1994 were fixed depending on the termination of spread and their X-coordinates were noted. For the intermediate imageries, the tail end X-coordinate was determined by interpolation depending on the variation of elevation. Based on the actual waterspread termination in the imagery, the probable tail end was selected near the interpolated value.

After editing and correcting all the eight imageries, the histogram of the imageries was analysed. Water spread area was calculated by multiplying the number of pixels by the size of one pixel (36.25 m x 36.25 m). The reservoir capacity between two consecutive reservoir elevations was computed using the prismoidal 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 area at the intermediate elevations (reservoir elevations on the dates of satellite pass) was obtained by linear interpolation. From the known values of original and revised areas at different elevations, the corresponding original and revised capacities were worked out. The cumulative revised capacity of the reservoir at the lowest observed level (92.196 m) was assumed to be the same as the original cumulative capacity (3247.02 M Cum) 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 revised capacities at the maximum observed level. The difference between the original and revised cumulative capacity represents the loss of capacity due to sedimentation in the zone under study. The calculations of sediment deposition are presented in Table - 1. The results show that the volume of sediment deposition in-between the maximum and minimum observed levels (104.446 m and 92.196 m) is 329.33 M Cum.

COMPARISON OF RESULTS WITH HYDROGRAPHIC SURVEY

Hydrographic survey of the Ukai reservoir was carried out in the year 1992-93. Only the revised capacity values at different levels (from the bed level of the river up to the FRL) were available. The detailed report of the survey was not available and the method of calculation of the revised capacity could not be ascertained. For the purpose of comparison of results of hydrographic survey with those of remote sensing, the revised capacity as per hydrographic survey at the intermediate elevations (reservoir elevations on the date of satellite pass) were obtained by linear interpolation as was done previously. The revised capacity at the lowest observed level (92.196 m) was assumed to be equal to the revised cumulative capacity (2619.56 M Cum) as reported by the hydrographic survey. Above this level, the revised capacity was calculated based on the remote sensing analysis 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 - 2. The plots of the original and the revised capacity as per hydrographic study and as per the remote sensing analysis are presented in Figure - 1.

DETERMINATION OF SEDIMENT DEPOSITION PATTERN

In the calculation mentioned above, the amount of sediment deposition has been quantified without reference to location of deposition. Using the GIS techniques, the grid-wise depth of sediment deposition within the zone of study can be evaluated. The revised water spread image of each date was convoluted with a high pass filter to obtain the boundary (contour) of the spread area. Using the eight contours of the spread area, the digital elevation model of the revised land surface was prepared by interpolation. The original contours of the reservoir were available and were digitized and the original digital elevation model was prepared on similar lines. The revised DEM was subtracted from the original DEM to obtain the depth of sediment deposition within the submergence area of the dam.

CONCLUSION

The conventional techniques of sediment quantification are cumbersome and time consuming. With the introduction of remote sensing techniques, it has become very cost-effective and convenient to estimate the sediment deposition in the various zones of a reservoir. Multi-temporal satellite data are extremely useful in determining sedimentation pattern in a reservoir. A generalized methodology is used for the identification of water pixels in the reservoir spread area thereby avoiding the need of subjective interpretation.

For the Ukai reservor, the cumulative volume estimated by remote sensing at reservoir level 104.446 m is 7086.86 M Cum. The original volume at this level was 8043.64 M Cum. Therefore, the loss in capacity in 21 years is 956.78 M Cum. This works out to 7.3 ha-m/100 sq km/year. At the time of planning the reservoir, the sedimentation rate was assumed to be 1.49 ha-m/100 sq km/ year. However, based on the hydrographic survey carried out 20 years after the dam construction, the Govt. of Gujarat had estimated the siltation rate to be 8.14 ha-m/100 sq km/year. It is thus seen that the rate worked out using remote sensing is of the same order as estimated by the use of hydrographic survey.

Quantification of reservoir sedimentation using remote sensing data is highly sensitive to the correct interpretation of the water spread area. Since the spread area is considered as lumped in the calculations, a small mistake in its interpretation at some point in the reservoir affect the final results. However, using the remote sensing technique in conjunction with GIS, the depth of sediment deposition in the reservoir can be found out. In this case, mis-interpretation of water spread boundary at some point in the reservoir do not affect the whole of analysis since the location of spread is taken into consideration.

A major limitation of the remote sensing based approach is that the sedimentation in the portion below the lowest and above the highest observed water levels can not be determined. The sediment deposition in the reservoir above the highest observed level is generally negligible. However, significant deposition occurs at the bottom of the reservoir and this can not be determined using remote sensing. This limitation is not significant since the zone of interest of sedimentation analysis, from the point of view of operation, is the live storage zone only. However, if sediment deposition pattern is required for the whole of the reservoir, hydrographic survey for the water spread area at the lowest observed elevation can be carried out and its results can be combined with the results of remote sensing. This reduces the extent of hydrographic survey analysis.

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Table - 1

Calculation of Sediment Deposition in Ukai Reservoir Using Remote Sensing

Date of Satellite Pass	Reservoir Elevation (m)	Original Area (Mm^2)	Revised Area (RS) (Mm^2)	Original Volume (Mm^3)	Revised Volume (RS) (Mm^3)	Original Cumulative Volume (Mm^3)	Revised Cumulative Vol. (RS) (Mm^3)
03.11.93	104.446	565.674	489.61	1358.99	1217.19	8043.65	7714.32
17.12.93	101.828	473.866	440.68	875.09	832.95	6684.66	6497.13
30.01.94	99.865	418.293	408.18	425.44	407.29	5809.57	5664.18
21.02.94	98.819	395.283	370.88	381.29	360.25	5384.12	5256.89
15.03.94	97.823	370.496	352.59	932.07	877.90	5002.83	4896.64
28.04.94	95.092	312.901	291.30	338.80	315.76	4070.76	4018.74
20.05.94	93.967	289.555	270.18	484.95	455.96	3731.97	3702.98
11.06.94	92.196	258.392	244.94			3247.02	3247.02

Table - 2

Comparison of Results of Hydrographic Survey with Remote Sensing

Date of Satellite Pass	Reservoir Elevation (m)	Revised Volume (HS) (Mm^3)	Revised Volume (RS) (Mm^3)	Revised Cumulative Vol. (HS) (Mm^3)	Revised Cumulative Vol. (RS) (Mm^3)
03.11.93	104.446	1100.32	1217.19	7192.16	7086.86
17.12.93	101.828	800.69	832.95	6083.18	5869.67
30.01.94	99.865	412.49	407.29	5282.49	5036.72
21.02.94	98.819	380.69	360.25	4870.00	4629.43
15.03.94	97.823	979.53	877.90	4489.31	4269.18
28.04.94	95.092	364.62	315.76	3509.78	3391.28
20.05.94	93.967	525.60	455.96	3145.16	3075.52
11.06.94	92.196			2619.56	2619.56

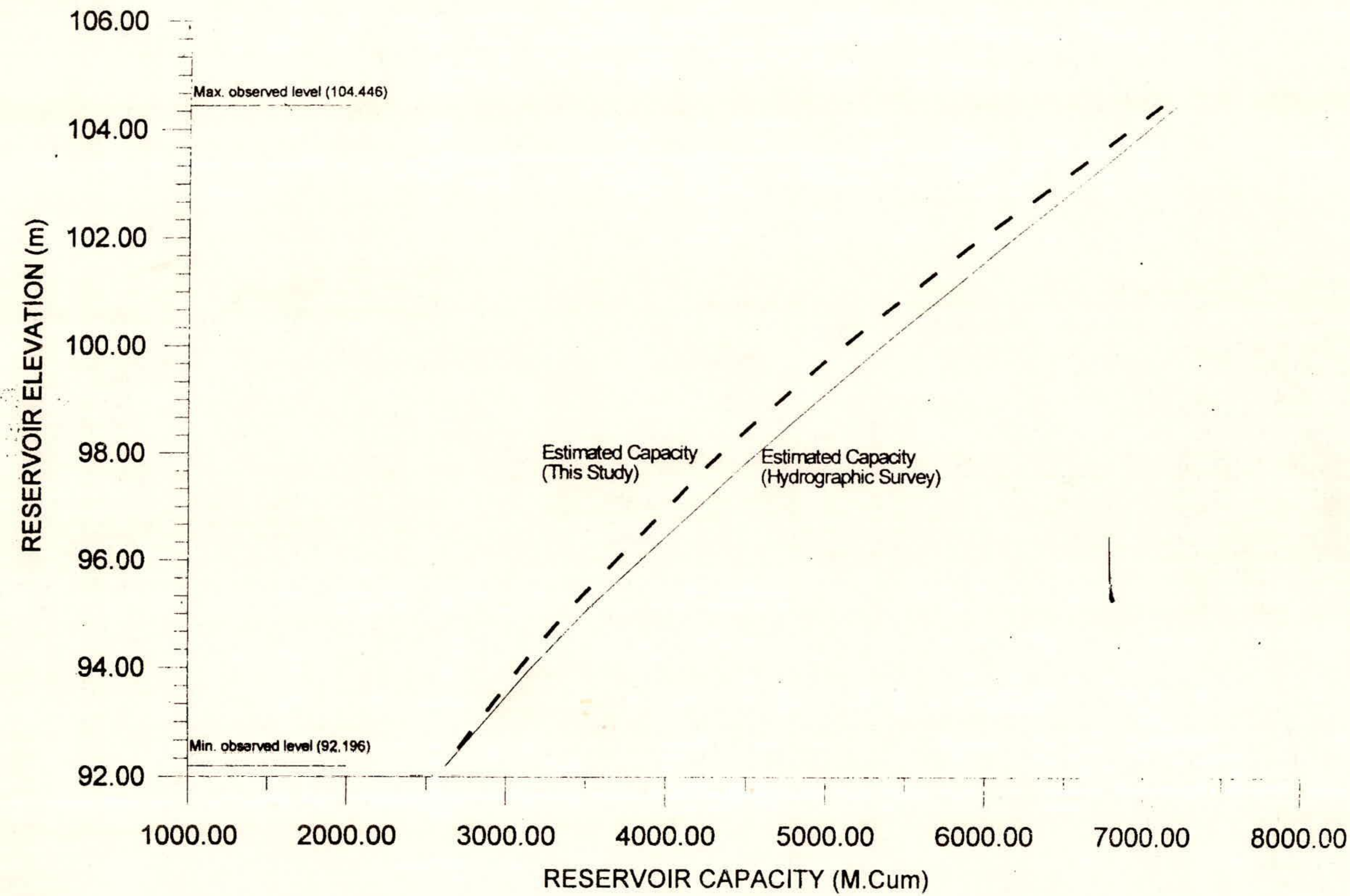

Fig. 1[illegible] : Comparison of Results (RS) with Hydrographic Survey