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Application of RS Data for Reservoir Sediment Profiling using Latin Hypercube-One at Time (LH-OAT) Technique

R. K. Jaiswal[1*], T.R. Nayak[1], Sanjay K Jain[2], A.K. Lohani[2]
[1]Scientist, National Institute of Hydrology, CIHRC, WALMI Campus Kolar Road Bhopal (M.P) India
*E-mail: rkjaiswal_sagar@yahoo.co.in
[2] Scientist, National Institute of Hydrology, Jal Vigyan Bhavan, Roorkee (Uttarakhand) India

Abstract
Assessment of reservoir sediment and its distribution are essential for irrigation releases, reservoir operation and assessment of soil conservation measures in the catchment. The empirical area reduction method suggested by Borland and Miller, 1960 is commonly used to determine sediment prediction based on limited data from reservoirs in USA. In the present study, an attempt has been made to optimize the parameters (C, m and n) of empirical area reduction method using Latin Hypercube, one parameter at a time (LH-OAT) technique for determination of sediment distribution in Ravishankar Sagar reservoir situated on river Mahanadi in India having gross storage of 909.54 Mm^3 and used mainly for irrigation purposes. The results obtained from optimized sediment distribution were compared with observed distribution through hydrographic survey (HS-2003) and further used to predict future sediment in reservoir. The proposed optimization technique conferred root mean square error of 10.79 Mm^3 in comparison with conventional technique which provided the same as 11.85 Mm^3 when both were compared with hydrographic survey. The best-fit revised water spread line/curve obtained from remote sensing results was by extrapolating in dead storage zone to determine new zero elevation and further computation of revised capacities at different levels. The results of remote sensing approach (RS-2003) were used in optimization technique to compare with hydrographic survey and found a close agreement of proposed remote sensing approach for determination capacity loss in dead storage zone also.

Keywords*:* "Reservoir sedimentation", "empirical are reduction method", "optimization", "digital image processing", "Latin hypercube-one at time"

Introduction
The deposition of water-borne sediments carried away/eroded from different parts of watershed is a universal phenomenon can be considered the most critical environmental hazard for reservoirs in modern time (Jain and Kothyari, 2000) with the loss 0.72% loss of storage every year in India). According to an estimate, reservoirs in the world loose an average one percent of their capacity each year (WCD, 2000). Apart from loss of capacity sediment deposit in reservoir also increased flood risks, interruption in hydropower generation, downstream river bed degradation, deterioration of water quality, increased complexity in reservoir operation, maintenance lead to increase in associated cost (Siyam et al., 2005; Annandale, 2006; Smith & Pavelsky, 2009; Sreenivasulu & Udayabaskar, 2010). The sediment storages in the dam reduce the delivery of sediment downwards that causes huge repercussion for the ecosystem and coastal development and affect river geomorphic processes (Woodward, 1995; Syvitski, 2003; Vorosmarty et al., 2003 etc.). The assessment of sediment distribution and its profile through estimation of revised capacities at different levels can be carried out either by conventional methods of bathymetric survey and inflow-outflow methods or recently developed approach of digital image processing of remote sensing data. The conventional methods of reservoir sedimentation assessment are costly, cumbersome and risky, therefore cannot be conducted frequently, while remote sensing approach cannot be used for assessment of revised capacities in dead storage zone as reservoir levels seldom go below dead storage level. Gopinath et al 2014 presented a reservoir sediment assessment study on Malampuzha reservoir, a multipurpose reservoir in the South Indian state of Kerala with the help of

bathymetric survey. The analysis suggested that the reservoir capacity is reduced from 226 Mm^3 to 205.19 Mm^3 in 55 years.

Emadi & Kakouei (2014) used Shuffled Complex Evaluation (SCE) algorithm for determination of optimize parameters of empirical area reduction method and RMSE was used as objective function. They found that the objective function has reduced from 62% to 48% in calibration and verification periods respectively. The conventional and remote sensing methods are useful to determine sediment deposition after certain point of time. From review, it may be summarized that remote sensing approach is widely used for assessment of revised capacities in live storage zone. But it is also necessary to determine possible future sediment profile of reservoir for a fixed total sediment deposit considering the present/original profile. Determination of future profile is helpful to decide dead storage level during planning stage and modification in reservoir operation plan for efficient planning after deposition of sediment. The sediment distribution in a reservoir is generally computed with the help of empirical area-reduction method suggested by Borland and Miller, 1960. In this method, the parameters C, m and n of this method are computed with the help of original area-elevation-capacity curve of the reservoir. In the present study, a methodology has been suggested to determine revised bed level from the data obtained using remote sensing scenes and optimize parameters C, m and n using Latin Hypercube-One Parameter at a Time (LH-OAT) method. The results of the analysis have been compared with conventional method of Borland and Miller, remote sensing approach and bathymetric survey.

Empirical Area-Reduction Method

The empirical are-reduction method is based on the principle that the sediment distribution in a reservoir at different levels depend on the shape of the reservoir. The main equation suggested in this method can be written as:

$$S = \int_0^{y_0} A dy + \int_{y_0}^{H} K a dy \tag{1}$$

where, S is the total sediment distribution during the period of life, A is the reservoir area at different height, dy is a small height increment, a is the approximate area of sediment, H is the total height of reservoir and K is a proportionality coefficient can be computed with the help of equation 2, which is the ratio of original reservoir area and sediment area at new zero elevation.

$$K = \frac{A_0}{A_P} \tag{2}$$

Where, A_o and A_p are the original and relative sediment areas respectively at new zero elevation. The empirical area-reduction method suggest that based on sediment distribution, a reservoir can be divided into any of four types of shapes namely gorge, hill, flood plain and lake. When capacities of a reservoir at different depths are plotted on a log-log scale, the reciprocal of slope suggest the type of reservoir (Table 1(a) and Fig. 1(a)). For determination of sediment at different levels, Borland and Miller further gave distribution pattern for different types of reservoirs with the help of standard dimensionless curves (Fig. 1(b)). In this graph, at any relative depth which is ratio of height from river bed to the total height (FRL-River bed); the relative sediment area (Ap) can be determined for a particular type of reservoir. The relative area can also be determined with the help of following equation:

$$A_P = C p^m (1-p)^n \tag{3}$$

Where C, m and n are the constant can be determined based on type of reservoir given in the table 1(b). Once, the constant K is computed for new zero elevation, the sediment area at any depth above this new zero elevation can be estimated as $K*A_p$ for different relative depth, while below new zero elevation it is equal to original reservoir area. Fendresky et al (2014) applied empirical-area reduction for determination of sediment pattern in Marron reservoir in Iran and observed that by calibrating the parameters of this method error rate may decrease from 34% to 24% and concluded that the parameters of this method should be optimized for other region as this was primarily developed based on information gained from a limited number of dams (30 dams in America). Therefore in this study, an attempt has been made to optimize the parameters C, m and n for a reservoir in India using an optimization technique of Latin Hypercube one parameter at a time (LH-OAT).

Table 1(a): Classification of reservoir (Borland and Miller, 1960)

Reciprocal of slope	Reservoir type	Standard Classification
Up to 1.5	Gorge	IV
1.5 to 2.5	Hill	III
2.5 to 3.5	Flood Plain	II
3.5 to 4.5	Lake	I

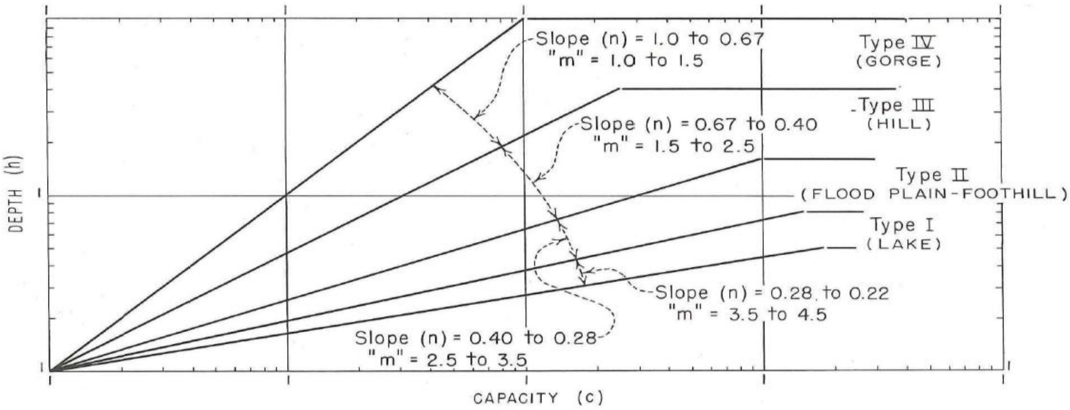

Figure 1(a): Determination of type of reservoir (Produced from Borland & Miller 1956)

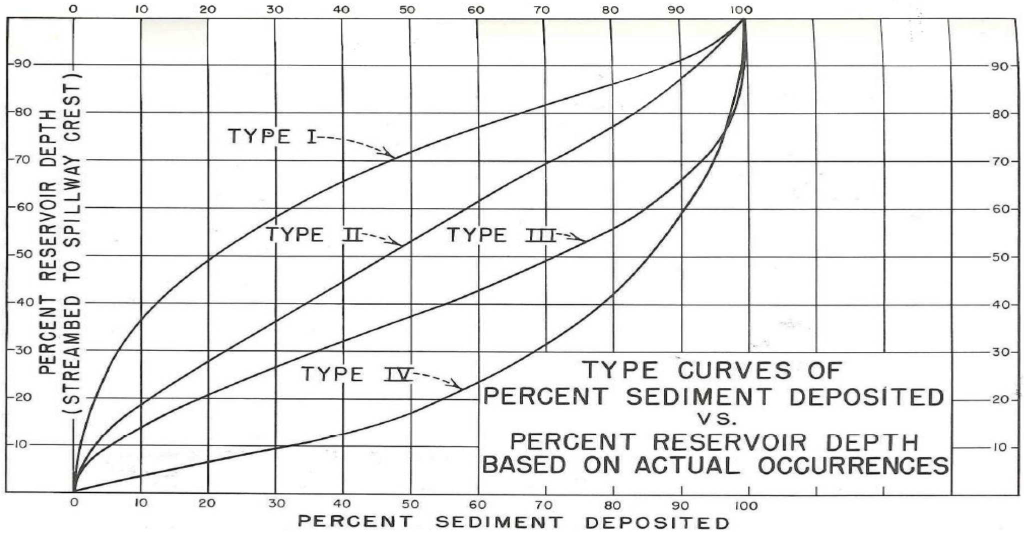

Figure 1(b): Sediment distribution in different reservoirs (Produced from Borland & Miller 1956)

Table 1(b): Constant C, m and n for empirical area-reduction method

Type	C	m	n
I	3.1470	1.5	0.2
II	2.3240	0.5	0.4
III	15.882	1.1	2.3
IV	4.2324	0.1	2.5

LH-OAT Optimization Technique

The Latin-Hypercube, one at a time method is used to optimize the parameters *C*, *m* and *n* for determination of relative sediment areas at different levels. This method is used to generate a reasonable sample from a collection of distributed multidimensional field. The Latin Hypercube Sampling was first presented and explained by McKay et al in 1979 (McKey et al 1979) and used for solving the problem of uncertainty for a particular class of problems (Wyss and Jorgensen, 1998). McKay el al (2000) has compared random, stratified and Latin Hypercube sampling random variables in Monto Carlo studies and found that the Latin Hypercube improved simple random sampling when certain monotonous conditions hold and it appeared to be a good method for selecting values of input variables. Zhang and Pinder (2003) applied Lattice sampling which is a special case of Latin Hypercube sampling (LHS) for groundwater flow and transport and found that LHS realization is not affected by seed and reduces the computational effort. Flores et al (2010) compared Latin Hypercube and random sampling techniques to sample soil hydraulic and thermal properties and concluded that LH based approach yielded less variance in the estimate of ensemble moments of all sizes. In the LH sampling whole sampling space or probability distribution is split into n intervals of spaces or probabilities in such a way so that exactly one observation lies in each interval (Hung 2013). The one at a time method has been used in optimization where the value of one parameter is changed as per LH keeping other parameters constant to examine all combinations that can prevail in the system.

Study Area & Data Used

The Ravishankar Sagar dam is constructed on river Mahanadi in Dhamtari district of Chhattisgarh state. The Ravishankar Sagar dam is one of the major dams of Multipurpose Mahanadi project, which consists of Pairi, Ravishankar Sagar, Moorumsilli, Dudhawa, Sondur and Sikasar reservoir. The base map of the study area has been presented in Fig 2. The Ravishankar Sagar Reservoir project was designed with the following objectives: Ravishankar Sagar dam was designed to convert existing 'Protective' Irrigation of Kharif paddy in about 1,82,500 hectare (1,47,500 hectare in Mahanadi old command and 35,000 hectare New area) to 'Productive' irrigation by providing timely, reliable and equitable supply, drinking water to Raipur and Dhamtari, power generation and industrial water supply to Bhilai Steel Plant. The gross storage capacity of Ravishankar Sagar reservoir is 909.54 Mm^3. The original area-elevation-capacity table and revised area-elevation-capacity table obtained from hydrographic survey in the year 2003 were used to compute the optimized parameters of empirical area reduction method. The results of remote sensing survey conducted in the similar period were used to demonstrate the capability of this method to estimate and extrapolate revised capacities of a reservoir.

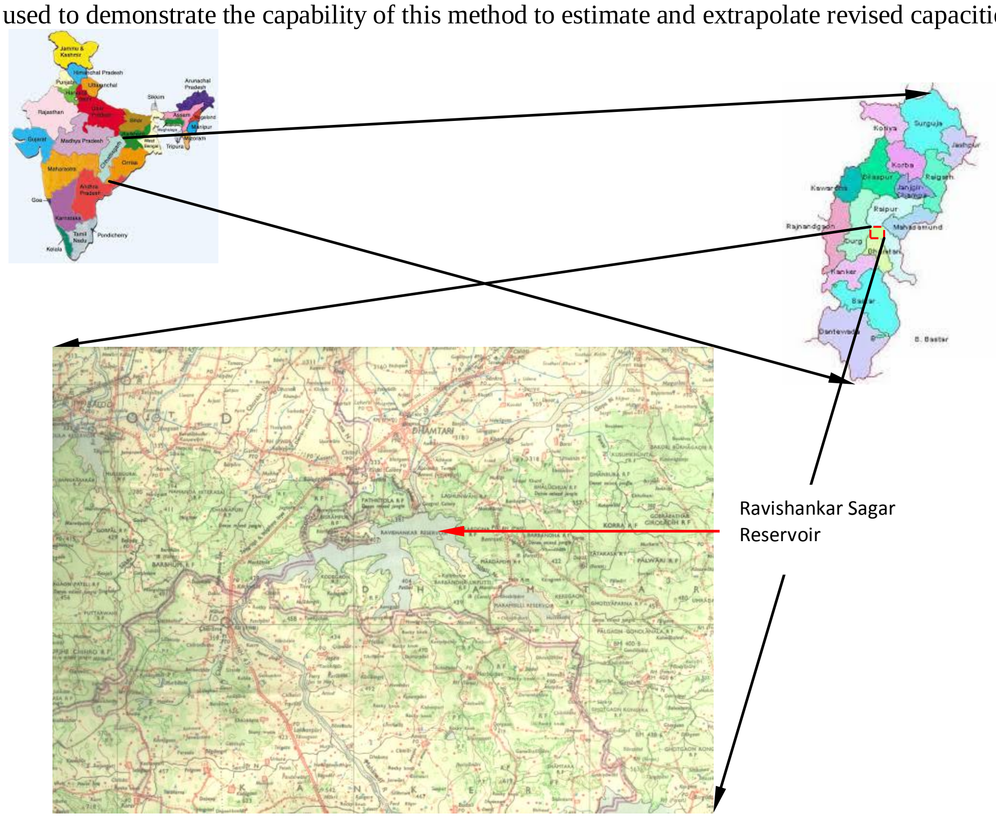

Figure 2: Location map of Ravishankar Sagar reservoir in Chhattisgarh State (India)

Methodology

The LH-OAT method has been used in the present study to optimize the parameters C, m and n of empirical area reduction method. Firstly, the original elevation and capacities were plotted on log-log paper to determine the type of reservoir and parameters C, m and n for Ravishankar Sagar reservoir. The profile of revised bed was then determined using conventional methodology proposed in this method. Now, considering the normal distribution of parameters, the LH-OAT method has been applied in which one parameter is considered for optimization keeping other constants and revised profile of sediments is obtained. A computer program was developed in FORTEAN, where, the parameters C, m, n were changed one-by one and revised profile were determined considering appropriate revised bed level based on trial & error method. For doing this, each time for value of C, m and n a revised bed level is assumed and taking these, revised sediment volume at highest flood level was computed and compared with actual sediment volume obtained from hydrographic/remote sensing survey. If the difference between actual sediment volume and computed sediment volume was within limit (0.5 Mm^3 in this case), the sediment profile is computed else next revised level is considered. If the computed revised sediment did not converge with actual sediment, then next combination of C, m and n were using LH-OAT sampling and best selection which gave the minimum difference between observed and computed total computed sediment has been selected for that reservoir.

Application of Remote Sensing Data

The estimation of revised capacity with the help of digital image analysis of remote sensing data is possible to determine revised water spreads at different levels, which in turn give the sediment amount in different levels of reservoir but only in live storage zone. In this study, an attempt has been made to apply remote sensing data for computation of sediment pattern in dead storage zone by extrapolation of best-fit line of revised water spreads with reservoir levels and determine new river bed and revised volumes in dead storage zone which in turn gave the volume of total sediment. The digital image processing of multi-date remote sensing data using normalized deviation water index, band ratio etc were carried out. The revised water spread then worked out using slicing of processed remote sensing images. A graph was plotted between reservoir levels and revised water spreads at different levels and best-fit line/curve was fitted to determine the new bed levels. The revised water spread areas obtained from this analysis was used to compute total revised sediment at H.F.L. Using this, total volume of sediment, the optimized parameters of C, m, n, sediment profile and revised capacities were computed as presented in earlier section. The results of computed revised capacities were compared with the capacities obtained from remote survey to assess the use of remote sensing methodology for determination of revised bed and sedimentation in dead storage zone of reservoir.

Analysis of Results

In the present study, an attempt has been made to optimize the parameters C, m and n of empirical area reduction method for Ravishankar Sagar reservoir built on river Mahanadi in Chhattisgarh state of India. In the analysis, first the conventional method has been applied in which the parameters of empirical area reduction method were determined using standard set of procedure suggested by Borland and Miller. In the next attempt, the parameters C, m and n were optimized using LH-OAT technique considering all the parameters are normally distributed in space. In the study, the remote sensing results have also been used to assess the suitability of extension of revised water spread best-fit curve in dead storage zone.

Conventional method

The results of hydrographic survey in the year 2003 confirmed that 28.20 Mm3 of volume has been lost at H.F.L. and to determine revised bed or sediment profile using conventional method, the slope of elevation and capacity were determined to assess the shape of valley. For Ravishankar Sagar reservoir, the slope of best-fit line of heights and original capacities values on log-log scale was computed and found as 0.04 which indicate it is a gorge shape valley. For gorge shape valley, the value of C, m and n were taken as 1.486, 0.10 and 2.50 respectively. The distribution of this volume was computed using conventional values of C, m and n that led to new zero elevation (revised bed level) as 331.50 m and revised capacity of reservoir at HFL may be 882.09 Mm3.

LH-OAT Optimization method

In the study, LH-OAT technique has been applied for optimization of parameters C, m and n of empirical area reduction method and new zero elevation for given sediment deposit (28.20 mm3) was found as 2.1, 2.4 and 1.8 respectively. The revised river bed and capacity at HFL using these values have been computed as 327.50 m and 881.59 Mm3 respectively. The original capacity, revised capacity curve from hydrographic survey (HS-2003), conventional and optimized methods has been presented in Fig 3. The root mean square error have been computed to compare the results of conventional and proposed optimization method and found their values as 11.85 and 10.79 Mm3 respectively that confirmed the suitability of optimization technique.

Remote Sensing Approach

The remote sensing approach of estimation of revised capacities is used to compute sediment loss in live storage zone of reservoir. In the study, an attempt has been made to find out a methodology to estimate revised capacities in dead storage zone using remote sensing approach. In order to obtain the new zero elevation (revised bed level), the revised water spreads and reservoir levels obtained from study (Jaiswal et al, 2009) were plotted and the best fit line/curve was extrapolated in the dead storage zone to determine new zero elevation and revised water spread at different levels. The following best-fit line has been obtained when revised water spread areas were plotted against reservoir levels.

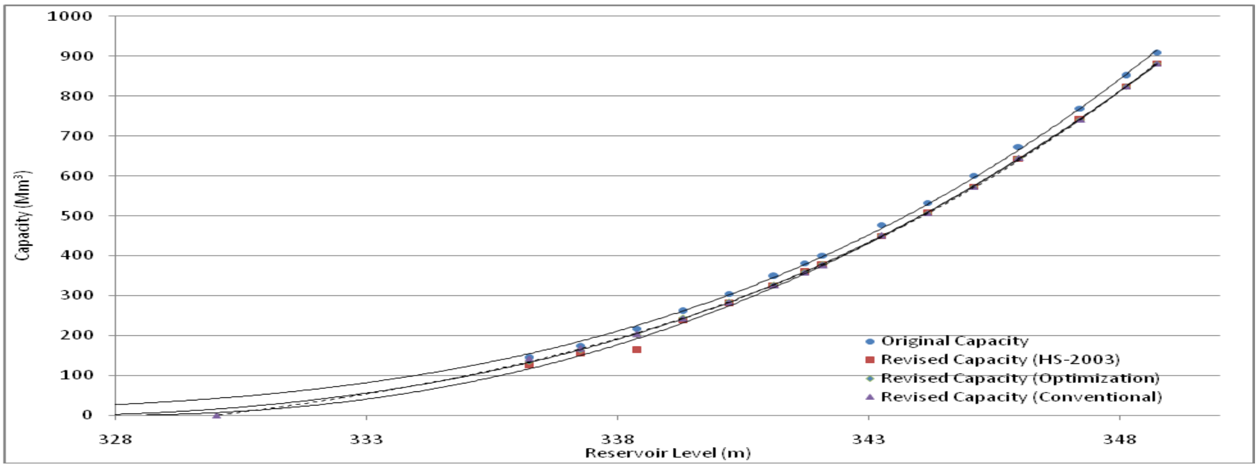

Fig. 3: Original and revised capacity from hydrographic survey, conventional and optimization technique

$$A_r = 521.26 * Y - 169156.5 \quad (4)$$

where, A_r is the revised water spread in hectare and *Y* is the reduced level of reservoir in meter. The revised water spreads obtained from remote sensing approach were to compute revised capacities and further to compute the gross capacities at different levels of Ravishankar Sagar reservoir using trapezoidal formula. The revised capacities obtained from this were compared with hydrographic survey and optimization technique. From the analysis of best-fit curve based remote sensing approach, it is found that revised bed level in the year 2003 is 330.22 m and total 30.58 Mm^3 has been lost which is near to the estimate from hydrographic method. From the analysis, it can be concluded that extrapolation of best-fit curve of revised water spread obtained from remote sensing approach can be used to obtained loss of storage in dead storage zone also. The LH-OAT based optimization technique then used to determine sediment profile for deposition of 30.58 Mm^3 sediment volume obtained from remote sensing approach. The values of C, m and n were obtained as 2.1, 3.5 and 2.9 respectively with revised river bed as 328.30 m. The original capacity, revised capacity (RS-2003) and optimized revised capacity for 30.58 Mm^3 depicted in Fig. 4. The root mean square error of sediment profile obtained from remote sensing based sediment deposition and conventional approach may be 13.86 Mm^3 that suggest that proposed methodology for determination of revised bed from extending curve in dead storage zone can be used in case of remote sensing analysis.

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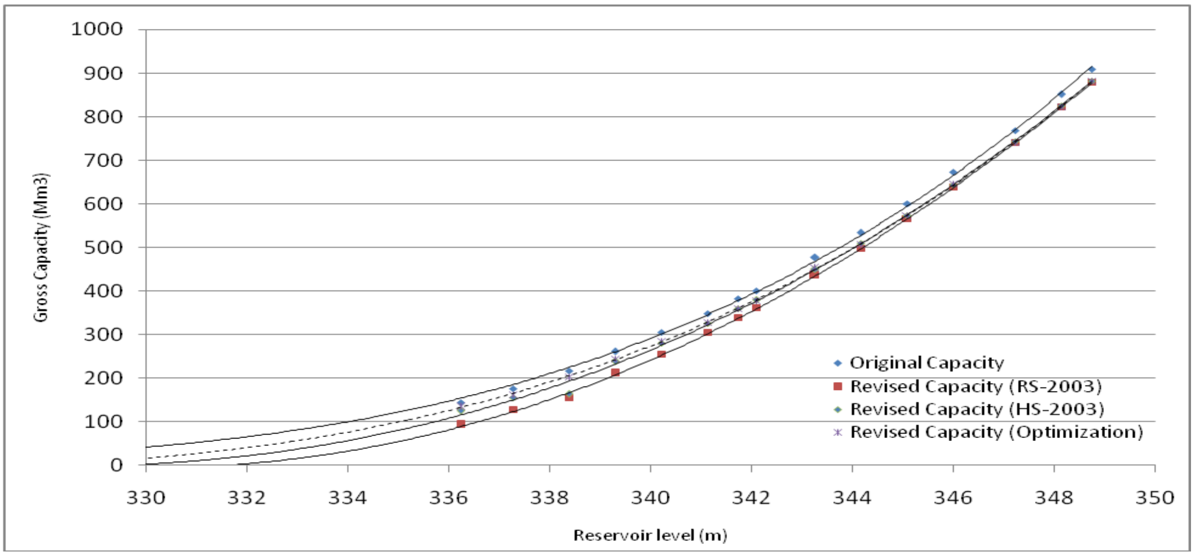

Fig. 4: Original and revised gross capacity from hydrographic survey, remote sensing and optimization technique

Discussion

The conventional empirical area reduction method proposed by Borland and Miller are based on results from reservoirs of USA, which some time may not give appropriate results in other part of world. The suggested method of optimizing parameters C, m and n using LH-OAT technique may provide profile more close to observed profile from hydrographic survey. The root mean square error of conventional and LH-OAT technique were found as 11.85 and 10.79 Mm3 respectively which shows the superiority of proposed method over conventional technique. It is therefore recommended to use optimization technique for getting sediment profile for any future period of time. In the present paper, an attempt has been made to use multi-temporal remote sensing data to determine revised water spread areas and in turn the revised capacities in dead storage zone by extrapolating revised water spread curve. The sediment profile for predicted revised sediment volume at HFL were computed using optimization technique and root mean square error of 13.86 Mm3 was able to concluded that remote sensing approach can be used to determine sediment in dead storage zone also. Future prediction of sediment using optimization technique for future periods of 2020, 2040 and 2060 will be helpful to modify reservoir operation plan as per predicted sediment in different zones of reservoir.

Conclusions

Assessment of reservoir sediment and its profile is important for water resources managers to efficient reservoir operation and modification of releases as per available capacities. In the present study an attempt has been made to optimized parameters C, m and n of empirical area reduction method using LH-OAT in which all parameters were considered as normally distributed and one-by-one considered for optimization. The analysis has been carried out for Ravishankar Sagar reservoir situated on river Mahanadi in Chhattisgrah state of India having gross storage of 909.54 Mm3. The results of hydrographic survey conducted in the year 2003 have been used as input in a program developed in FORTRAN where sediment profile were determined using conventional and proposed optimization method for empirical are reduction method. It may be concluded that the revised elevation-capacity curve obtained from optimization technique have close resemblance with observed hydrographic survey with lesser root mean square error than conventional technique. In the study, an attempt has been made to extrapolate revised water spread curve in dead storage zone to determine revise river bed and total sediment for reservoir. The revised sediment loss from remote sensing was observed as 30.58 Mm^3 (0.033% of gross capacity) as compared to 28.20 Mm^3 (0.031% of gross capacity) by hydrographic survey indicated use of extrapolation of revised water spread curve in dead storage zone which otherwise not possible in remote sensing approach.

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