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ESTIMATION OF REVISED CAPACITY IN RESERVOIRS OF CHHATTISGARH STATE USING DIGITAL IMAGE PROCESSING TECHNIQUE

Part-II

(Kharkhara, Sondur, Matiamoti, Mongra and Paralkot Reservoirs)

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE 247 667
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PREFACE

The soil erosion, transportation and subsequent deposition are natural processes reduce useful storage, availability of water, operation and overall benefits from reservoir. The sediment also influences downstream water quality, conveyance capacity of canals, biotic life and ecosystem. The assessment of revised capacity which is an indicative of sediment deposition is essential to determine present availability of water, modification in reservoir operation, necessity and intensity of soil conservation in the catchment. To estimate reservoir sedimentation conventional techniques like hydrographic survey, inflow-outflow method, bathymetric survey are used which are time consuming, laborious, risky and cumbersome. An alternative of traditional methods, the digital image analysis of remote sensing data is commonly used which is less time consuming, needs less manpower, less risky and economical. The remote sensing (RS) based technique of revised capacity estimation is essentially based on principle that the deposition of sediment reduces the water spread at any level which can be demarcated with the help of image processing of multi-band RS data in geographic information system (GIS) software. The revised water-spread areas determined from image analysis and elevation data are used to compute reduced volume of water which ultimately provides revised cumulative capacities on these levels. The computed revised capacities can be compared with the original capacities to find out changes in capacity and percentage losses between these levels.

In the second year of study, an attempt has been made to compute the loss of storage capacity and sedimentation in Kharkhara, Sondur, Matiamoti, Mongra and Paralkot reservoirs of Chhattisgarh state in India by digital image processing approach of remote sensing data. The study is being carried out jointly by Central India Hydrology Regional Centre (CIHRC), National Institute of Hydrology, Bhopal and State Water Data Centre (SWDC), Water Resources Department (WRD), Govt. of Chhattisgarh, Raipur. This report is prepared by Sri R. K. Jaiswal, Sc-D, as P.I., with Co-P.I. as Dr. T. R. Nayak, Sc-E & Head, Sri R. V. Galkate, Sc-E, Sri T. Thomas, Sc-D and Sashi P. Indwar, Sc-C from CIHRC, Bhopal and Sri Akhilesh Verma, Deputy Director as P.I. and Sri J. N. Vishwakarma, A.E., Sri S. K. Verma, Sub Engineer, Sri S. K. Shukla, Sub Engineer, Sri T. L. Chandrakar, Sub Engineer as Co-P.I. from SWDC, WRD Raipur under the guidance of Dr. N.C. Ghosh, Coordinator & Sc-G, NIH Roorkee is the second part of sedimentation report.

Sharad K. Jain
(Director)

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ABSTRACT

The soil eroded from different parts of catchment flow through channels and rivers deposited in dead as well as live storage zones of reservoir duo to reduced velocity of flowing water under natural hydrological process. But, the rate of sedimentation in reservoirs and lakes is accelerated due to environmental degradation, lack of conservation measures, change in land use, deforestation etc. Presently, the live storage capacity of large dams in India is 225.14 billion m^3 out of which 1.95 billion m^3 capacity of reservoirs is being lost annually. Reservoir surveys are necessary to get more realistic data/estimate regarding the rate of siltation and to provide reliable criteria for studying the implication of annual loss of storage over a definite period of time with particular reference to reduction of intended benefits in the form of irrigation potential, hydropower, flood absorption capacity and water supply for domestic, industrial and other uses and periodic reallocation of available storage for various pool levels.

With the introduction of remote sensing techniques in the recent past, it has become convenient and far less expensive to quantify sedimentation in reservoirs and to assess its distribution and deposition pattern. Advantages of using remote sensing data are that it is highly cost effective, easy to use and requires lesser time in analysis as compared to conventional methods. The spatial, spectral and temporal attributes of remote sensing provide valuable synoptic and timely information regarding the revised area after the occurrence of sedimentation and sediment distribution pattern in the reservoir. The digital image analysis of multi date remote sensing data have been used to determine revised water spreads at different water levels of reservoir which in turn compute revised capacities and cumulative capacities in these levels.

The present report is the second part of the study in which Kharkhara, Sondur, Matiamoti, Mongra and Paralkot reservoirs in Chhattisgarh state were chosen for assessment of revised capacities using remote sensing data. The normalized difference water index (NDWI), band ratio (BR) and false color composite (FCC) along with field truth verification were used to differentiate water pixels from rest of image. The reservoirs seldom go below dead storage level (DSL), due to which remote sensing technique is generally used to determine loss in storage in live storage zone only. This weakness was overcome in this study by backward extension of best-fit curve between reservoir levels and revised water spreads to get revised river bed. This method was verified with the help of revised capacity curves obtained from conventional and optimized empirical area reduction method. In the optimization method, the parameters *C*, *m* and *n* of this method were optimized using Latin Hypercube, one at time (LH-OAT) technique.

The results of analysis showed that 8.41Mm^3 storage from 169.54 Mm^3 original capacity in Kharkhara reservoir during 51 years, 12.54 Mm^3 from 198.1 Mm^3 in Sondur reservoir during 28 years, 4.59 Mm^3 from 29.56 Mm^3 in Matiamoti reservoir during 24 years, 3.67 Mm^3 from 48.55 Mm^3 in Mongra reservoir during 10 years and 3.53 Mm^3 from 66.25 Mm^3 of gross storage in Paralkot

reservoir during 37 years have been lost due to deposition of sediment in different zones. The rate of sedimentation in all ten reservoirs taken for two years study vary between 0.032 $Mm^3/100\ km^2/yr$ in Tandula reservoir and 0.086 $Mm^3/100\ km^2/yr$ in Sondur reservoir where size of catchment vary approximately from 120 km^2 to 3335 km^2. In the second year study, the parameters C, m and n of empirical area reduction method were optimized using Latin hypercube, one parameter at time (LH-OAT) technique to determine sediment profile and revised river bed for Gondli reservoirs. The profile obtained from conventional and optimized methods were compared with the profile obtained from remote sensing (RS) technique and establish the application of this method for determination of revised river bed and loss of storage in dead storage zone of reservoir.

CHAPTER -1: INTRODUCTION

1.0 General

Water resources are very vital renewable resources essential for the survival and development of any society and necessitate assessment and management of the quality and quantity both spatially and temporally. The precipitation is the main source of water in India but uneven spatial and temporal distribution compels water resource managers to collect surface water flowing through the rivers by constructing a barrier across the river by forming reservoir. The capacity of reservoir reduces continuously due to entry of eroded soil carried by water, wind, ice and movement of particles due to gravity force. A huge quantity of sediment is deposited annually by Indian rivers in lakes, reservoirs, estuaries, bays and oceans. Loss of storage capacity due to reservoir sedimentation affects ability of water and operation schedules (Biswas et al 1999). Sedimentation process in reservoir is a natural phenomenon and almost every reservoir is bound to suffer a loss in their storage capacity potential because of silt load, for long period of time.

The continuous sediments deposition reduces the reservoir storage and channel conveyance (canals) for water supply, irrigation, cover fish spawning grounds, reduce downstream water quality and cause extensive disturbance to streams. The suspended sediments make water turbid and reduce sunlight penetration affects biotic life. The sediment settlement to the bottom of water bodies buries and kills the vegetation and changes the ecosystem. When a size of reservoir is relatively small compared to the mean annual runoff (MAR) (less than 10%) and the sediment yield is value is higher, then siltation of reservoir will occur in a short period of time as compared to large reservoirs which requires more time to filled with sediment. The sedimentation rate and ultimate storage capacity of small reservoirs will then be controlled by flushing or sluicing of sediment through wide low level outlets at the time of floods or the rainy season (ICOLD 2009). The dam construction can vary the flow regime and sedimentation load of the river at downstream by changing flood peaks and durations, also by trapping large amounts of sediment. It is of uttermost significance to be aware of yield, composition and rate of sediment in reservoir. These information allow water resource managers to estimate approximate lifespan of a reservoir and decide future course of action against reservoir sedimentation, water shortage and river bank breaches.

1.1 Factors Influencing Sedimentation Process

The sediments come from the fluvial channel system primarily settle in reservoir due to lowering of water speed near the obstruction in the form of dam. The sedimentation deposition process derived from drainage channels is largely affected by vegetated area, soil erosion, floods and storms, rain water runoff carrying sedimentation and the properties of sediment transported along the water (Sreenivasulu at al 2012). The factors affecting the sedimentation yield process in drainage are given below:

- Topography (geomorphology);
- Type of soil and its geological formation.
- Soil coverage (like vegetation, apparent rocks and open soil area).
- Soil management (cultivation process, grazing of grass by animals, forest cutting, building constructions etc).
- Climatic factor like precipitation quantity, frequency and intensity.
- Topography of the area.
- Nature of the drainage channel network like density, slope, shape, size and the configuration of channels.
- Surface runoff, Sediments features like granulometric, mineralogical etc and channels hydraulics.

All the sediment brought down by river water to the dam does not settle in the water spread and periphery of reservoir. A significant part of it flows down the reservoir while distribution of remaining part depends on topography of water spread, reservoir capacity and inflows, catchment characteristics, reservoir operation and types of structures including arrangement and operation of sluices etc.

1.2 Effects of Reservoir Sedimentation

Sediment storage in reservoir behind dams can have large presumption for ecosystem and coastal growth downstream of large river systems, as inferior sediments are deposited which will influence river and coastal geomorphic functions (Syvitski, 2003; Vorosmarty et al., 2003; WCD, 2000; Woodward, 1995). The main adverse impact of reservoir sedimentation is reduction of capacities that lead to reduction of availability of water for designated uses and reduction of crop production, power generation, domestic water supply and ultimately the overall economics of the region and cost benefit ratio of reservoir. The reduced capacity may cause increased flood risks in the downstream of reservoir due to less absorption of water in live storage and flood zones. When the sediment laden water enters into the dam’s intake like penstock, river sluice and gates etc, it impedes navigation and swimming and clogs electromechanical equipment at dams and increase corrosion of equipment.

The sedimentation of reservoir also has environmental, quality and ecological ill effects also. The sedimentation process in reservoir may cause serious water quality deterioration which is not fully explained or surveyed yet. The floods and torrents derives large amount of water which may contain nutrients, agro-toxic, bacteria, algae human and industrial waste etc. When these substances enter in the reservoir undergoes several changes lead to affect the downstream water quality resulting underwater decay and reservoir stratification. Such effects must be previewed, assessed and conciliated at the time of planning, execution, construction and reservoir operation time. The sediment particles entering into the bed of reservoir form delta along the river coarse lead to the deformation of river channel that becomes strangled. In narrow channels delta gradually increases, which increases reservoir backwater and increases floods in areas surrounding to reservoir. The deposits of the sedimentation in reservoirs modify the bed level thus lead to the degradation of habitats for most fishes and other aquatic species, which causes loss of some species and strong one survives only. It also modifies breeding grounds for mosquitoes and other nuisance species and disease vectors. The suspended sediment load in reservoir reduces the penetration of sunlight, thus retarded photosynthesis process that reduces the oxygen level in water body. The greenhouse gasses are released into the atmosphere after the biomass decomposes through aerobic and anaerobic vegetation in reservoir occurs, either slowly or rapidly. These greenhouse gasses are widely consulted as the main reason of human-induced global climate change, which contribute to retrograde the thermal heating of low terrestrial atmosphere known as greenhouse effect (UNEP, 1997).

1.3 Techniques for Measurement of Reservoir Sedimentation

The reservoir sedimentation is natural process for all reservoirs whether big or small but remains invisible in the significant part of its life. The regular monitoring of sediment deposition is necessary to know current available capacity, loss in storages and need assessment of soil conservation measures in the catchment. The state of sediment deposition may allow to determine the probable lifespan of a reservoir and to take proper measures against reservoir sedimentation, shortage of water, river bank and coastal erosion. The reservoir sediment or assessment of revised capacities can be grouped in two broad categories i.e. conventional and non-conventioanal techniques.

1.3.1 Conventional techniques

The conventional techniques include inflow-outflow technique and hydrographic survey, are cumbersome, clumsy, time consuming, uneconomical and involve huge manpower. Sometimes these conventional methods approximately take up to three years to complete just one survey of a major reservoir (like Hirakud, Sardar Sarivar, Bhakra etc.) so cannot be done frequently . Some of the conventional methods are life threatening but able to give detail sediment pattern in different zones and their location also. In the inflow-outflow method, the measurement of sediment inflows from different streams to the reservoir and outflow from reservoir are computed with the help continuous monitoring of discharges and sediment sampling. The mass balance equation is used to determine the amount of sediment deposited in the reservoir. The measurement location should be sufficiently nearer to the reservoir periphery and proper care must be handled to execute the inflows and outflow sample analysis before it meets the tenable channel downstream.

The hydrographic survey is done with the help of echo sounder with transducer, differential geographic positioning system (GPS), field computer and reliable power supply (Munir et al 2014). Two methods are commonly used for hydrographic surveys includes (1) the contour method and (2) the range line method. The contour method involves making of suitable scale contour map of the reservoir and contour interval similar to the contours at the time of survey. The difference in capacity between two studies presents the loss of capacity due to sediment deposition during that period. In range method, survey is performed in the selected limits across the reservoir and this gives the basis for the estimation of cubic contents between ranges. The contour method of survey is universal type which is applicable for all types of reservoir (small or large) while range method is limited to relatively straight reaches.

1.3.2 Non-conventional techniques

The substitute of lengthy, cumbersome and time consuming conventional methods is the latest techniques of digital image analysis of multi temporal remote sensing data. This method requires less time, need less manpower and economical than other conventional methods but having disadvantage of not providing sediment deposit in dead storage zones. The synoptic and repetitive viewing capability of remote sensing data is used for determination of revised water spreads at different levels of reservoir which in turn provides revised capacities at different levels. The image analysis capability of GIS software can be used effectively for differentiating water pixels from rest of the images.

1.4 Distribution of Sediment

The reservoir elevation-area-capacity is basically used for determination of storage in reservoir, irrigation planning and reservoir operation. The understanding of the distribution of sediment in a reservoir is essential for fixing sill levels of the outlets and the penstock gate levels to dodge inopportune loss of services when sediment load is eloquent factor. The revised distribution can also be used to modify reservoir operation plan and assess need of soil conservation measures in the light of sediment entry in to the reservoir. The distribution of the deposits should be determined to permits the assessment of the limit to which various allocations of the storage is disturbed by sediment accumulation. The distribution pattern of various reservoirs depends on lots of factors like valley slope, reservoir length, and size of particles in suspended sediment, ratio of capacity-inflow and reservoir operation. The main river tributaries also influence the distribution pattern depending on their magnitude of inflow, shape and location.

Two methods namely the empirical area reduction and area incremental methods are commonly used for approximate estimation of the sediment distribution pattern. Borland and Miller (1958) categorize the distribution pattern of sediment in a various reservoirs into four standard classes. The data presented by them shows that there is a definite relationship between percent of total depth of a reservoir to the percent of total volume of reservoir sediment presents for each of the four different reservoir types depends on physical shape. The type of the reservoir is classified by plotting the reservoir depth on ordinate and capacity on abscissa in logarithmic coordinates or log-log scales. The plotted curve draws as a straight line, wherever some reservoirs may have a shape responsible in two straight lines. The reciprocal of the slope of the line presented the reservoir type. The curve indicating a rapid increase in capacity compared to depth signify large basin type reservoir, whereas a less increase in the relationship signifies gorge type reservoirs**.**

1.5 Objectives

As sedimentation deposited in dead as well as live storage zones of reservoir affects normal reservoir operations and intended benefits taken into consideration during design, it is necessary to monitor reservoir sediment, resultant profile and revised capacities at regular intervals. The present study for estimation of revised capacities of reservoirs in Chhattisgarh state to determine present rate of siltation with the following objectives:

- Estimation of revised capacities of reservoirs and trend assessment in selected reservoirs
- Sediment profile for selected reservoirs using conventional as well as optimization technique
- Knowledge dissemination and development of awareness

In the part II of reservoir sedimentation study, Kharkhara, Sondur, Matimoti, Mongra and Paralkot, reservoirs were selected for sedimentation study using remote sensing data.

CHAPTER- 2: REVIEW OF LITERATURE

The review for present study consists of reservoir sediment and its impact, assessment of reservoir capacity and techniques for sediment profiling. A detailed review on all these aspects have been carried out and outlined here.

2.1 Reservoir Sedimentation and its Impacts

The problems of reservoir are wide and varied including Loss of storage, blocking of outlets, over flowing, delta deposition, channel aggradation, interference in navigation, earthquake, abrasion, shoreline erosion, ecological problem, downstream consequences of bank erosion, increase of bank height, increase in scouring, environmental issues etc (Rao et al 2014). The gradual loss of storage volume which results in reduced capability to provide water for irrigation, hydropower production and other uses, as well as to intercept floods and regulate the flow. When the sediment deposits near to structure, it may block the outlets or even compromise the safety of the dam. The sediment passing through the turbines causes abrasion of mechanical equipment, decreasing its power generating efficiency and ultimately loss of production time during its repair (Petkovsek & Roca, 2014). The total control on sediment deposition in reservoir is not possible as it is a universal phenomenon (Jain and Kothyari, 2000). But, the rate of sedimentation in reservoirs and lakes is accelerated due to environmental degradation, lack of conservation measures in catchment, change in land use, deforestation, urbanization and industrialization (Jaiswal et al 2010).

The life of a reservoir starts reducing soon after its commissioning due to continuous deposition of water-born sediments eroded/washed from all parts of watershed (Jaiswal et al 2009). The range of problems caused by reservoir sedimentation is varied and wide. Apart from loss of capacity, increased flood risks, interruption in hydropower generation and downstream river bed degradation; other problems such as degradation of water quality, increased complexity in reservoir operation and maintenance lead to increase in their associated cost (Kothyari et al., 2002). A broad estimate of soil erosion in India showed that about 5334 million tones of soil is being lost every year, which means, soil erosion is taking place at the rate of 16.35 tones/ha/year (Narayana and Ram Babu, 1983), which is more than the permissible soil loss tolerance value of 4.5 - 11.2 tones/ha/year (Singh et al, 1981). As a result, it is widely viewed that, nearly 20 % of the live storage capacity of major and medium sized reservoirs of India have been silted up by the end of the year 2000, which means a loss of irrigation potential of about 60,000 ha every year due to silting. An analysis of sedimentation survey in respect of 43 major, medium and minor reservoirs in India indicated the variation of sedimentation rate between 0.003–0.28 Mm^3/100 km^2/year for major reservoirs, 0.002–0.11 Mm^3/100 km^2/year for medium and 0.01–0.02 Mm^3/100 km^2/year for minor reservoirs (Shangle, 1991). The results of a survey in the year 2012 from 122 reservoirs in India indicated that 0.44% of storage is being lost every year due to sediment which accumulates in dead as well as live storage zones of reservoir (Rao et al 2014)

2.2 Revised Capacity Assessment

The reservoir sediment or loss in capacities of a reservoir can be determined with the help of conventional methods such as hydrographic survey and inflow-outflow method or advance technique of digital image classification of remote sensing data. The conventional method of reservoir sedimentation survey has been in practice for quite long time in India and elsewhere. The conventional methods of reservoir sedimentation are time consuming, costly, cumbersome and require lot off manpower, therefore cannot be used frequently. But the synoptic and repetitive viewing capacity of remote sensing sensors and the ability of image processing with geographic information system (GIS) can be used to model bathymetry and the spatial distribution of sediments (Evans et al 2002). The data obtained from the remote sensing platforms by virtue of their repetitive and synoptic coverage and computer aided analysis make significant contributions in understanding and monitoring the environmental processes. Basically, multi-date satellite remote sensing data provide information on elevation contour areas directly in the form of water-spread areas. Any reduction in reservoir water-spread area at a specified elevation estimated from the satellite data is indicative of sediment deposition.

Hanumantha Rao et al (1985) adopted visual interpretation of enlarged MSS images to estimate the water spread at eight different levels of the Sriramsagar reservoir. Suvit et al (1988) used digital image analysis technique in which density slicing of Landsat MSS near-IR (0.8- 1.1 μm) data were used to extract the water spreads of the Ubolratana Reservoir of five different dates. Singh et al (2010) used digital image processing technique of remote sensing data to assess the loss in reservoir capacity & sedimentation of Ujjani reservoir (also named as Yashavant Sagar reservoir) on river Bhima, in Sholapur district of Maharashtra state, India having catchment in of 14, 856 km^2. It was found that there was loss of gross storage of 498.38 Mm^3 from 1977 to 2004 (i.e. 27 years). Bhatti et al (2011) carried out research work for computation of suspended sediment engrossment in surface waters using of ALOS and ASTER satellite data. They combined the multispectral data and optical modeling to minimize the lack of ground truth data.

Goel et al, (2002) assessed the reservoir sedimentation of Bargi Reservoir M.P, India using digital image processing data & satellite image data. The steps of analysis were to Import, visualized and geo-referencing the satellite data, identification of water pixels, removal of discontinuous pixels, removal of extended tail and channels, derivation of revised contours and at last calculation of revised capacity. After estimating the sedimentation they concluded that the procedure to remove the discontinuous pixels and the derivation of contours has been considerably automated & the remote sensing technique is a time- and cost-effective and convenient approach to estimate the elevation-area- capacity curves for a reservoir. Panday et al (2013) estimated the reservoir sedimentation in Patratu Reservoir, Jharkhand, India using Satellite Remote sensing (SRS) technique. The sedimentation assessments was carried out using satellite data & reservoir water level data from 2006-2012. From the analysis, it has been found that the live storage of Patrau reservoir has reduced from 101.95 ha-m to 89.96 ha-m which is about 11.8% in 44 years.

Al Ansari et al (2013) In their used topographic maps of Mosul Reservoir of two different years i.e. 1983 and 2011 and applied Triangular Irregular Network (TIN) for the calculation of sedimentation rate and determining the reduction in storage capacity for live as well as dead storage of Mosul reservoir during its operational period. The TIN maps were used to compute the storage capacity and water-spread area for live storage and dead storage using Arc/GIS software. The reduction in storage capacity of the reservoir for the two surveys at different time represents total volume of sediment accumulated and reduction in water spread area for reservoir. Mandwar et al (2014) evaluated the performance of Reservoirs in Nagpur region using Satellite Remote Sensing (SRS) technique. In the study it has been found that the average rate of sedimentation of Nagpur region 5.22 ha-m/100km^2/year which is less than the rate given in iso-erosion map of that region by Singh et al, 1981. To predict soil loss the Revised Universal Soil Loss Equation (RUSLE) module can be used. At least two to three satellite remote sensing survey each of the reservoirs at the interval of five years span may be required for accurate assessment of rate of sedimentation. In addition to this Hydrographic survey can be conducted to assess the accurate rate of sedimentation of the reservoirs.

Javed et al 2016 estimated the sediment yield in the catchment of Govind Sagar in Lalitpur District, Uttar Pradesh (India) using IRS LISSIII data to analyze land use/cover characteristics besides drainage basin characteristics. In this study Sediment Yield Index (SYI) of Govind Sagar catchment has been estimated using surface derivatives and morphometric parameters using empirical formulae. Integration of results obtained from satellite data and morphometric analysis suggests that the catchment of Govind Sagar has very low rate of sediment yield i.e .0.07 ha-m/year indicating a gentle slope and sustainable land use practices in the catchment. Low sediment yield also suggests less erosion in the catchment area and healthy land use/cover scenario.

Ninija Merina et al 2016 evaluated the sedimentation carried out for Vaigai Reservoir situated in Tamil Nadu, India using image analysis of remote sensing in Arc GIS. Satellite Images of IRS-P6 LISS-III have been georeferenced with respect to topo-sheets and mosaic using Arc GIS 9.3.1. The gross storage capacity of Vaigai reservoir has reduced from 194.785 Mm3 to 162.620Mm^3 till 2012. Vaigai reservoir has lost its capacity by 32.164 Mm^3 in the year 2012 since its inception, i.e., its total sediment yield is 32.16 Mm^3 which is greater than the sediment yield of the year 2000, which was 28.252 Mm^3. The average annual silting rate for the years 1976, 2000 and 2012 are 8.52%, 14.50% and 16.51% respectively.

The ability to map and estimate water spread from satellite data is well understood and commonly used techniques include visual interpretation of satellite imagery, density slicing, and digital classification of water from other land uses for delineation of water bodies (Work and Gilmer 1976; Thiruvengadachari et. al 1980; Thiruvengadachari and Manavalan 1983; Jain & Goel 1993; Goel & Jain 1996; Mukherjee et al 2007; Rathor et al 2006; Thomas et al 2009; Jaiswal et al 2008; Jaiswal et al 2011; Narasayya et al 2012; Ninja Merina et al 2016 etc.).

2.3 Sediment Profiling in Reservoir

The deposition of sediment in reservoir is not uniform at all the storage zones and remote sensing technique has limitation of not capable to assess deposition in dead storage zone because reservoirs seldom empted below dead storage level. The hydrologic size is a primary factor influencing the rate of sediment accumulation (Brune, 1953) primarily responsible for determination of types of sediment management techniques required for a particular reservoir. The sediment profile can be determined by different conventional methods like empirical area reduction method (Borland & Miller, 1958; Lara, 1962) and area incremental method by Christiphano in 1953 also several optimization methods were proposed by different researchers (Amini et al 2010). Issa et al. (2015) studied four empirical and semi-empirical techniques proposed by Mohammadzadeh Habili et al. 2009, Mohammadzadeh Habili & Heidarpour 2010 and Kaveh et al. 2013 along with area reduction method. For assessment, these methods were reviewed and used to compute sedimentation depth and establishing the ASC curves for the Mosul dam reservoir (MDR), which is the biggest hydraulic structure, build on the River Tigris in northern Iraq. The results were compared with bathymetric survey data carried out in 2011 after 25 years of functioning of MDR. The comparison of the results for establishing the ASC curves presented that the method proposed by Kaveh et al. (2013) gave good relation with bathymetric output.

Mohammadiha & Emadi (2011) used conventional area reduction method for Golestan dam and adjudged a reduction of 10% on error estimation. Fendreski et al (2014) applied area reduction and incremental area methods for computation of sediment profile using conventional as well as optimized parameters which were then compared with hydrographic survey using error rate and standard error as goodness of fit criterions. From the analysis, it has been observed that error rate can be reduced from 34 to 23 percent by optimizing in area reduction method. Rahamanian & Banihashemi (2012) introduced a new shape function in the form of depth factor which is the ratio of volume of pyramid to the actual volume of water in the reservoir at that level based on the analysis of 42 dams in Iran. On the basis of analysis, it has been observed that these dams can be classified into three groups and cumulative sediment deposition was inversely related to variations of depth factor in height. To determine sediment distribution two empirical functions called depth shape function (DSF) and relative depth shape function (RDSF) were introduced to determine sediment pattern in nine reservoirs. From the analysis, it has been observed that the sediment pattern observed from new developed functions RDSF can predict relative sediment deposition and sediment deposition in a wide variety of reservoir geometries.

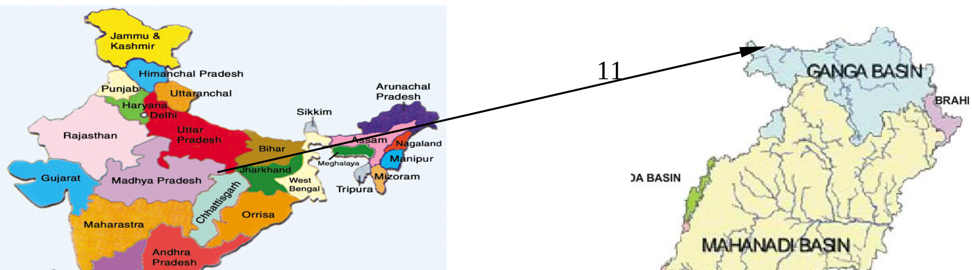
CHAPTER- 3: STUDY AREA AND DATA USED

The sedimentation analysis using remote sensing data has been carried out for Kharkhara, Sondur, Paralkot, Matiamoti and Mongra reservoirs of Chhattisgarh state as Part-II of the study.

3.1 Chhattisgarh State

The Chhattisgarh state is rich in water resources and large numbers of medium and major water resources projects have been created to harness extra surface water to cater irrigation, industrial and domestic demands. In the present study, some important reservoirs of Chhattisgarh state have been considered for reservoir sedimentation study using digital image analysis of remote sensing data. The total geographic area of Chhattisgarh state is about 1, 35, 194 km^2 formed on Nov 01, 2000 by partitioning from Madhya Pradesh state of India. The average rainfall in the state is around 1400 mm and about 90% of the total rainfall falls in the monsoon season. The Mahanadi, Godavari, Ganga, Narmada and Brahmani basins drain out the state and Mahanadi, Seonath, Hasdeo, Arpa, Indravati, Sabari, Leelagar, Hasdeo, Kelo, Son, Rehar, Kanhar, Pairi, Sondur, Sabari, Mand, Narangi etc. are important rivers which have a torrential regime characterized by high flow of water for three to four months during monsoon (June to September) during which around 80% of the annual runoff flows. The paddy in rabi and kharif season is the main crop of the state demands more storage of surface water due to large scale variability of rainfall and large demands of crops.

The state is called as rice bowl of India and surface water is prime source of irrigation to met demands of paddy crop, industrial and domestic water requirement. In order to meet various water demands of state, several major, medium and minor irrigation projects are commissioned and serving the state. Some of the important reservoirs of the state are Ravishankar Sagar, Tandula, Hasdeo – Bango, Sondur, Maramsilli, Kharkhara, Gondli, Paralkot, Dudhawa, Minimata etc. For the second part of the study, Kharkhara, Sondur, Paralkot, Matiamoti and Mongra reservoirs were selected by joint research group of Central India Hydrology Regional Centre, Bhopal of National Institute of Hydrology and State Water Data Centre, Raipur for estimation of revised capacity using digital image analysis of remote sensing in GIS environment. The base map of study area is given in the Fig. 3.1. All the reservoirs selected for the second part of the study are situated on important tributaries of river Mahanadi which is called the life line of Chhattisgarh state covers 50% of land in the state and supplies water for irrigation, drinking, industrial and other purposes.



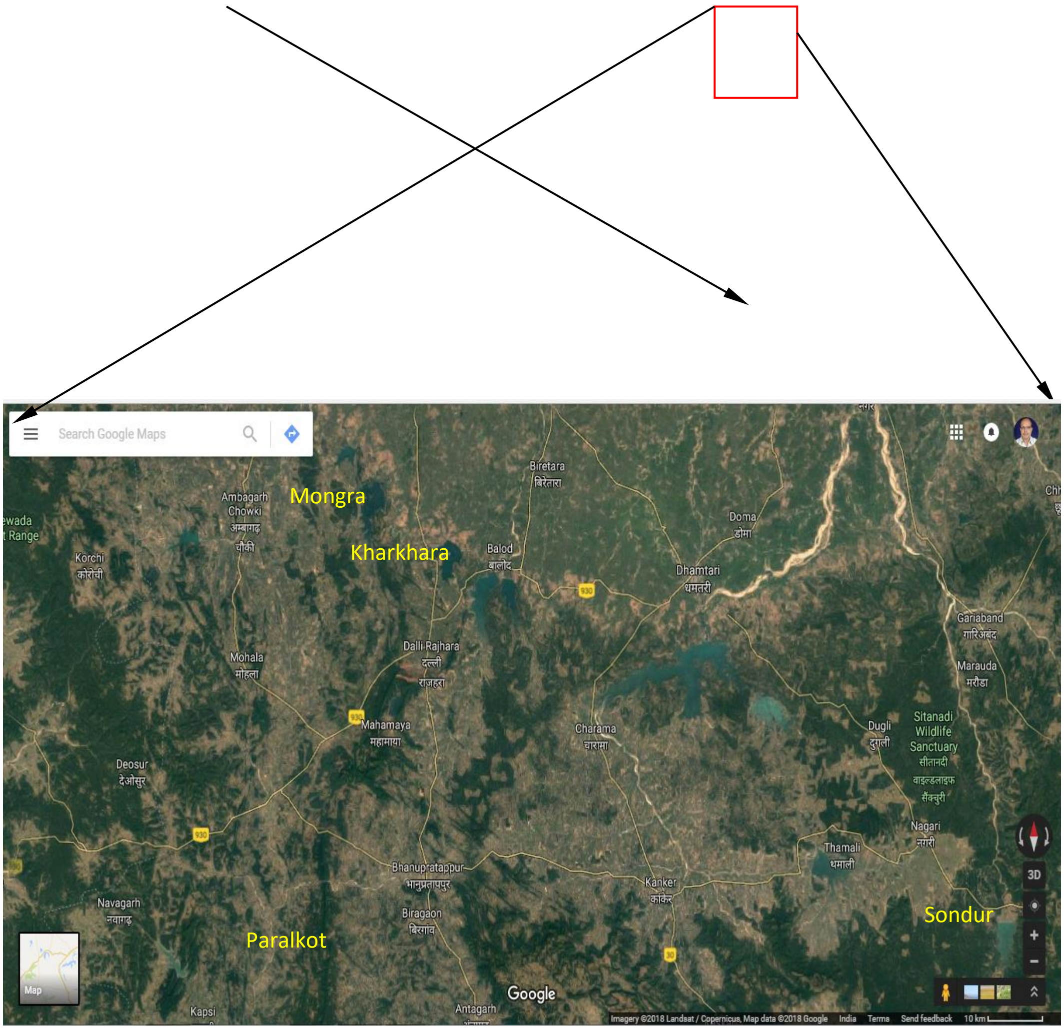


Fig. 3.1 Location map of Study Area

3.1.1 Kharkhara Reservoir

Kharkhara dam is situated at 80° 58’ 19” E longitude and 20° 48’ 00” N on river Kharkhara in Mahanadi basin near Balod city of Chhatissgarh. It is Major Irrigation Project completed in 1967. The Kharkhara dam is an earthen dam of 1463 m in length having design flood of 1133 cumec. The dam is designed to supply water for irrigation of 6939 culturable command area and part supply of water to Bhilai Steel Plant. A pictorial view of Kharkhara reservoir is presented in Fig. 3.2.

Fig. 3.2 Pictorial view of Kharkhara reservoir

3.1.2 Sondur reservoir

The Sondur Dam (Fig. 3.3) is located in Dhamtari District of Chhattisgarh and started its operation in the year 1988. The dam having gross storage capacity of 169.54 Mm^3 constructed on river Sondur River with catchment area up to the dam is 518 km. The dam was designed to irrigate 12260 ha kharif crop in Nagri tehsil of Dhamtari district, besides augmenting supplies in Dudhawa and Ravi Shankar reservoirs under Mahanadi Reservoir Project Complex

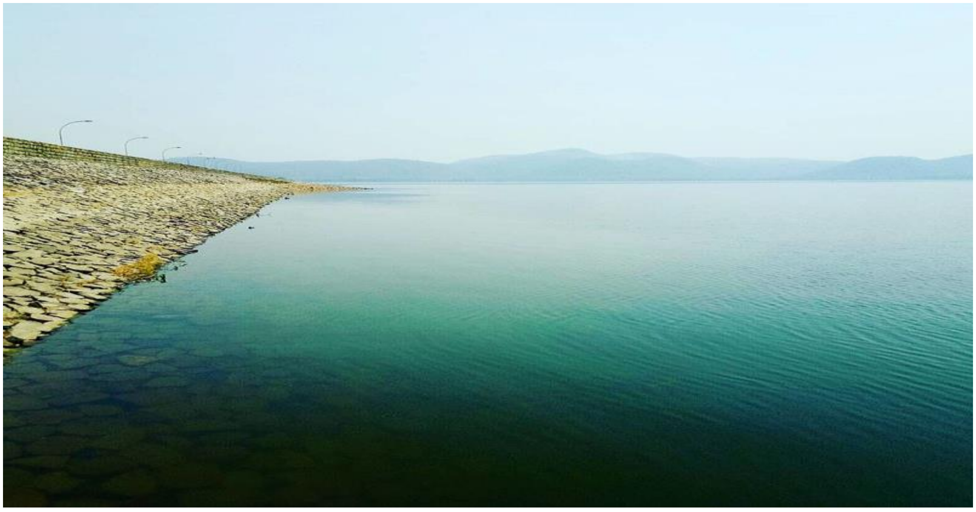


Fig. 3.3 Pictorial view of Sondur reservoir

3.1.3 Matiamoti Reservoir

The Matiamoti Nalla project is a medium irrigation project located in Rajnandgaon District of the State. The water supply source for the project has its ongoing in the Satpura hills from there it runs about 35.5 km to the dam site and eventually joints Shivnath River, a tributary of Mahanadi River. The Matiamoti Nala dam site is located at 80°56’30’’ E longitude & 28°53’12’’N latitude. The site is situated between two small hillocks in either side of the Moti Nala. A right bank main canal and distribution system irrigates culturable command of 5714 ha. This scheme also provides 300 M ft^3 drinking water to Rajnandgaon Municipal Corporation. The project comprises to 18.6 km long main canal and three distributaries with distribution systems to irrigate 5000 ha Kharif and 1500 ha Rabi crops. The goggle map of Matiamoti reservoir has been presented in fig. 3.4.

Fig. 3.4 Google view of Matiamoti reservoir

3.1.4 Mongra reservoir

The Mongra reservoir is constructed by stopping water through Mongra barrage situated on river Shivnath in Rajnandgaon district. The length of barrage is 155 m with 9 gates to pass 9726 cum/sec design discharge. The location map of Mongra barrage is presented in Fig. 3.5. The gross and live storage capacities of Mongra barrage are 48.55 and 32.05 Mm^3 respectively. The culturable command area of Mongra project is 9431 hectare in 43 villages of Ambagarh, Dongargaon and Rajnandgaon where more than 70% population is schedule tribes.

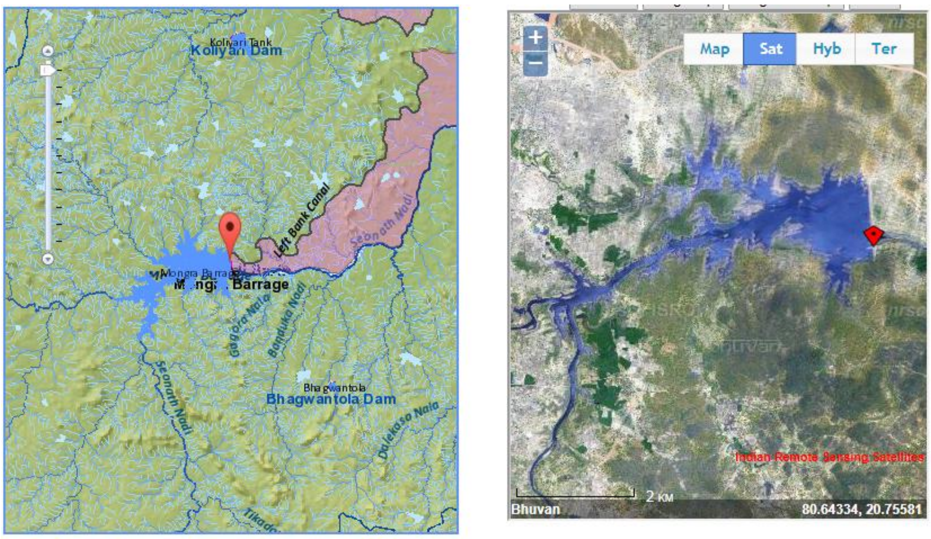


Fig. 3.5 Location map of Mongra barrage in Chhattisgarh (Source: India-wris)

3.1.5 Paralkot reservoir

The Paralkot reservoir is also known Kherkatta Reservoir, is a man-made lake about 12 km north of Pakhanjore in Kanker District situated in Goadvari Basin on river Deoda. The Paralkot dam is constructed on river Deoda in Godavari basin. The Paralkot dam is 1.2 km long earthen dam with ogee type of spillway of 232 m length to pass 974 m^3/sec design flood. The gross storage capacity of Paralkot reservoir is 66.25 Mm^3. The pictorial view of Paralkot reservoir is presented in Fig. 3.6.

Fig. 3.6 Pictorial view of Spillway of Paralkot dam

3.2 Data Used

The original elevation-capacity table of all reservoirs, characteristics values of reservoirs and reservoir elevations during the period 2015 to 2017 were used in second year of analysis. The original elevation-capacity tables of different reservoirs have been depicted in Table 3.1 to 3.5. The dates of pass of path 101 and row 57 of IRS satellite were identified for Kharkhara, Mongra and Matiamoti reservoirs, 102 and row 58 of IRS satellite for Sondur and MSS of Landsat for Paralkot reservoir were selected. The IRS data were procured from National Remote Sensing Centre Hyderabad while Landsat images were freely available on internet downloaded from USGS website. The date of acquisition, path-row and reservoirs levels for different dates used in the analysis have been presented in Table 3.6(a) to 3.6(e).

CHAPTER- 4: METHODOLOGY

4.1 General

The construction of barrier in the form of dam for storage of water causes siltation of reservoir due to reduction of speed of flowing water . The periodical assessment of capacity of reservoirs is necessary for determination of extent of degradation in the catchment areas, allocation of existing water for different purposes, determination of useful life of reservoir and rate of siltation etc. The basic principle of revised capacity estimation using remote sensing and GIS is that when the sediment deposits in a reservoir, its water spread get reduced with respect to its original area before impoundment (Fig. 4.1). The multi-date remote sensing data and capability of GIS software to delineate water pixels can be used to extract revised water spreads from rest of the image at different reservoir levels. The digital images of different dates are required to cover the whole range of live storage. The methodology for assessment of sediment through remote sensing and GIS is indirect method in which revised water spread at different reservoir levels are computed with the help of remote sensing data which in turn are used for estimation of revised capacities, cumulative capacities and loss of storages. The synoptic viewing and repetitive movement of satellite data are helpful in this regard.

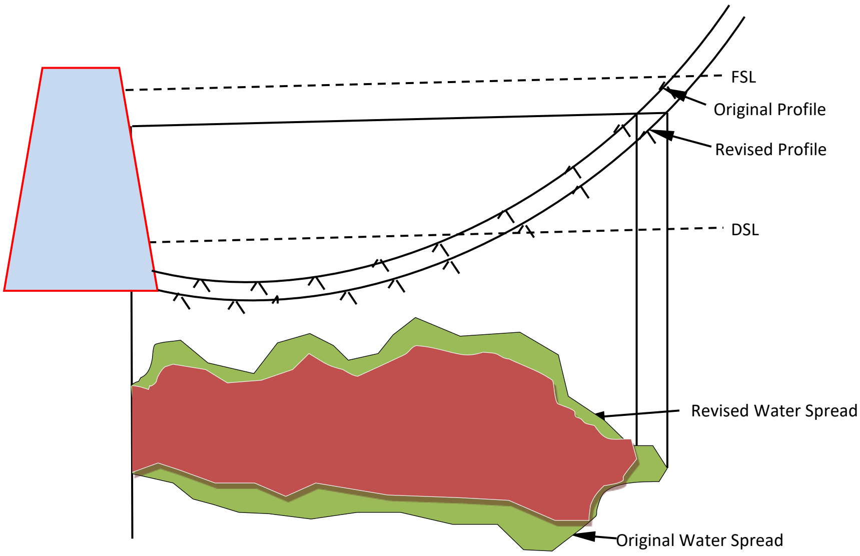


Fig. 4.1 Principle of assessment of sediment in digital image classification technique

The method of remote sensing does not directly compute the silt in the reservoir. It helps to determine the present storage capacity, which is compared with the original or designed capacity and the reduction in capacity over a period of time is attributed to silt deposition. The correctness of silt computation by this method was fully dependant of the rectification of the original area capacity table. If the accuracy of original survey is not of high quality and contained errors, then results of silt assessment based on comparison of outputs of original survey with satellite remote sensing (SRS) base or hydrographic survey may not give correct results of siltation in reservoir, hence it is suggested that SRS based sedimentation surveys be frequently carried out at regular intervals of 3 to 5 years. The methodology for digital image analysis of remote sensing data based technique of reservoir sediment assessment consists of preparation of GIS based base map, selection, procurement and import of satellite data, estimation of revised water spread, determination of revised capacities and losses from reservoir.

4.2 Preparation of Base Map in GIS

The satellite image scene in raw form are supplied either in raw format or geo-referenced with limited ground control points require atmospheric and earth curvature corrections. For using the images for any meaningful results and determine areas of different land features after image classification, it is necessary to geo-reference the images with survey of India toposheets and other cadastral maps of the corresponding area with the help of standard image processing software. This phenomenon is known as image rectification. The base map consisting drainage, roads, rail, canal network and important points based on topo-sheets and other reliable maps need to be prepared which subsequently used for geo-referencing of remote sensing data procured from National Remote Sensing Centre Hyderabad, the sole supplier of RS data in India. The ground control points should be easily identified on remote sensing image and of permanent nature.

4.3 Selection of Remote Sending Data

The IRS LISS III data of Indian satellite were used in this study and therefore, the different date of passes based on their temporal resolution and quality of scene were finalized from web site of NRSC. With the close look on reservoir levels and corresponding availability and quality RS data, seven to ten remote sensing scenes were selected for each reservoir in such a way so that these data can cover whole range of live storage at nearly equal interval. These selected data were procured from NRSC and used in the analysis. After importing, all the images need to be geo-referenced with the help of topo-sheets/maps so that they can be overlaid and linked with the latitude and longitude and the geographical area also can be determined. After geo-referencing, all the images can be cut down to small sizes to cover the water spread area of the reservoir and its surroundings.

4.4 Image Analysis

The remote sensing images represent information regarding the vegetations cover on the ground including agricultural surface, forest land, natural vegetation, waste land etc. and other features such as water bodies, road/rail network, built up land etc. Two methods of remote sensing data interpretation including visual and digital image analysis are commonly used for classification of image. The visual techniques are purely dependent on the interpretative capability of the analyst. In the digital image analysis, the, multi band data are processed in GIS software to get some known indices with the help of raster operation which ultimately distinguished water pixels from rest of the image.

4.4.1 Visual technique

It is purely based on the explicate capability of the analyst and this technique provide a facility of not using the information of different band (as in case LISS-III sensor data shows four band), after the visual result is obtained. Wet land around the periphery of the water spread area seems to very similar to water pixels & which makes very complicated for eyes to analysis whether the pixel near the periphery is to be named as land or water. The presence of clouds or noise in the scene near the periphery make difficult to compute actual water spread area.

4.4.2 Digital image analysis techniques

Remote sensing provides land resource data in the form of digital magnetic types and in different bands of the electromagnetic spectrum. For any given material, the amount of solar radiation that it reflects, absorbs, transmits, or emits varies with wavelength. This important property of matter makes it possible to identify different substances or classes and to separate them by their individual spectral signatures. In the visible region of the spectrum (0.4 - 0.7 μm), the transmittance of water is significant and the absorption and reflectance are low. The reflectance of water in the visible region scarcely rises above 5%. The absorption of water rises rapidly in the near-infrared (NIR) band where both, the reflectance and transmittance are low. The reflectance of various objects present on the earth is different than water and this reflectance recorded in digital format by the sensors mounted on satellite. The digital data obtained from the sensors can be used to extract water spreads at different levels. The normalized difference water index (NDWI), band ratio and slicing has been used to identify the water pixels in the images. The *NDWI* and band ratio (B*R*) for identification of water pixels can be written as:

$$NDWI = \left[\frac{GREEN - NIR}{GREEN + NIR}\right] \tag{4.1}$$

where, GREEN = Band-II data of IRS 1D/P6 satellite, NIR = Band IV data of IRS 1D/P6 satellite.

$$BR = \frac{NIR}{GREEN} \tag{4.2}$$

The slicing operation of the NDWI and band ratio images is carried out to extract water pixels from the rest of the image. In the slicing operation, the FCC, NDWI and BR images should be examined carefully where knowledge of spectral characteristics and ground truth information play an important role to decide the upper limit above which all the pixels can be classified as water.

4.5 Discarding of Extended Tail and Channels

The main river at the tail end of the reservoir and numerous small channels joining the reservoir from distinct directions around its periphery are also classified as water during digital image classification. However, the elevation of water in these channels and the main river can slightly higher than the water surface of a reservoir receiving inflow through perennial streams inflow. So, these extended tail and channels must be separated from the point of termination of spread. The choice of truncation point is subjective and may be depend on the difference between the water levels in the subsequent date scenes.

4.6 Computation of Revised Capacity

After extracting water spread area from rest of the image, the histograms were built to determined revised water spread directly. As water level in the reservoir seldom goes below dead storage level (DSL), in the present study a graph has been plotted between revised water spreads and reservoir levels. A curve has been fitted and extended backward to determine revised bed of reservoir. The reservoir capacity between two consecutive reservoir elevations was calculated using the prismoidal formula.

$$V = \frac{h}{3}\left(A_1 + A_2 + \sqrt{A_1 * A_2}\right) \quad (4.3)$$

where, V is the volume between two sequential elevations, A_1 and A_2 are the water spread areas at sequential elevations and h is the difference in the elevations. The revised cumulative capacities can be computed by adding the revised volumes between consecutive intervals which in turns used to estimate losses in revised capacities.

4.7 Comparison with Empirical Formulae

In the present study, the rate of sediment from reservoir has been compared with two following equations given by Khosla and Jogelkar (Mutreja, 1986 & Subramanya, 2008).

Khosla's Equation: $V_s = \frac{0.323}{A^{0.28}}$ (4.4)

Joglekar's Equation: $V_s = \frac{0.597}{A^{0.24}}$ (4.5)

where, V_s is the rate of sedimentation in $Mm^3/100\ km^2/yr$ and A is the catchment area in km^2.

4.8 Sediment Profiling

The empirical area reduction method proposed by Borland & Miller in 1959 and later on modified by several researchers. Conventionally, three parameters (C, m, and n) based on slope of elevation capacity best-fit line is determined which in turn provide sediment distribution for trial and error based revised river bed called zero elevation. The parameters of this method were suggested based on results of study from reservoirs situated in USA which sometimes may not be useful in other part of world. In the present study, the sediment profiles of few reservoirs were determined conventional as well as optimization techniques for deposition of sediment obtained from remote sensing analysis.

4.8.1 Conventional empirical area reduction method

When the total sediment deposition in the reservoir is known, the profile can be determined by empirical area reduction method and area incremental method. The empirical are-reduction method is based on principle that the accumulation and distribution of sediment has specific relationship with the shape of reservoir. The main equation suggested in this method can be written as:

$$S = \int_0^{y_0} A\, dy + \int_{y_0}^{H} Ka\, dy \qquad (4.6)$$

where, S is the total sediment distribution, A is the reservoir area at height y, dy is a small height increment, a is the approximate area of sediment, H is the total height of reservoir, y_o is the new zero elevation and K is a proportionality coefficient can be expressed by the following equation.

$$K = \frac{A_o}{A_p} \qquad (4.7)$$

where, A_o is the original area and A_p is the relative area at new zero elevation y_o. The methodology of empirical area reduction method consists of determination of reservoir's shape. The shape of reservoir is determined by plotting gross capacities on X-axis and respective reservoir depths on Y-axis in a log-log plot. The reciprocal of slope (m) is used to determine type of reservoir as given in Table 4.1 or Fig 4.2.

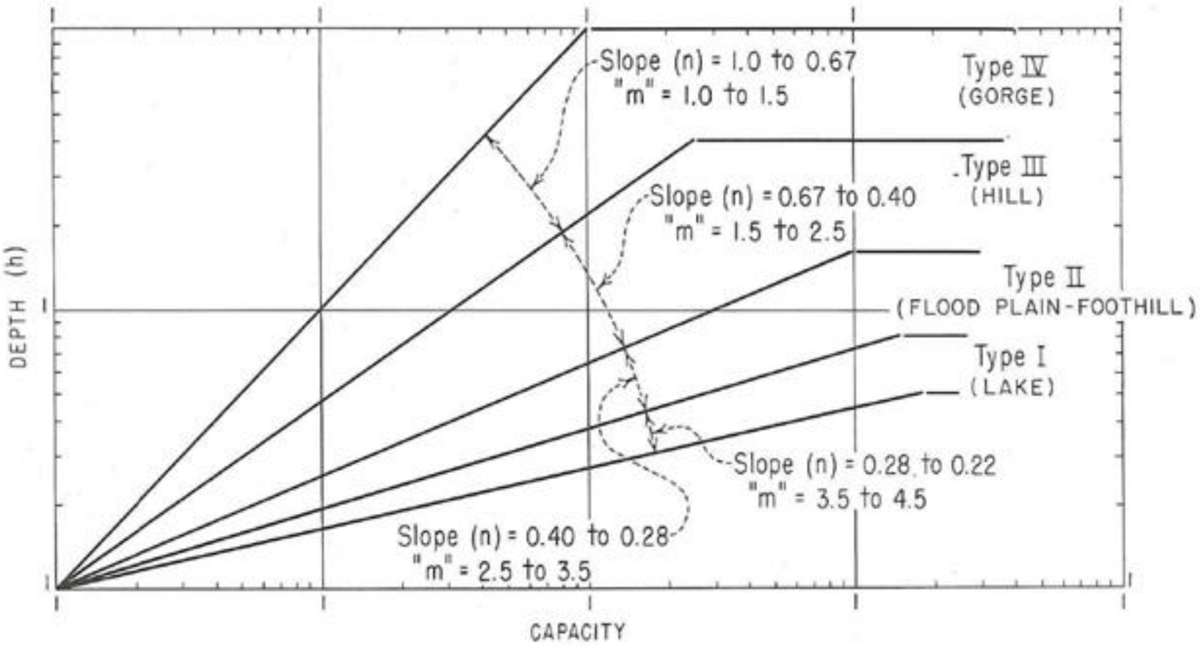


Fig. 4.2 Determination of type of reservoir (reproduced from Borland & Miller 1960)

The constants *C*, *m* and *n* of empirical area reduction method may be determined using Table 4.1. After determination of constants, a new zero elevation is assumed for a given sediment deposit and relative depths (*p*) for different elevations can be computed as the ratio of depth to total depth of reservoir. The relative areas (*Ap*) at different elevations are computed using following equation or Fig 4.3.

$$A_p = Cp^m(1-p)^n \tag{4.8}$$

Now, constant *K* is computed using equation 4.7. By multiplying *K* and A_p at different depths, the sediment areas can be determined which subsequently used to compute sediment volume between the levels using trapezoidal formula. The total sediment volume at HFL is then computed by adding subsequent sediment volumes between the elevations and compared with total desired sediment deposit. If computed volume is not near to the total sediment need to be deposited, the next new zero elevation is assumed and whole process is repeated again till difference between computed and needed sediment deposit come within the limit (Generally 10% or as decided). In the present study, an attempt has been made to apply conventional and optimization approach where total sediment deposit obtained from remote sensing approach for Gondli reservoirs. With the help of optimization where Latin Hypercube one parameter at a time (LH-OAT) were used to verify the use of revised water spread curve for determination of revised river bed and sediment deposit in dead storage zone in remote sensing approach.

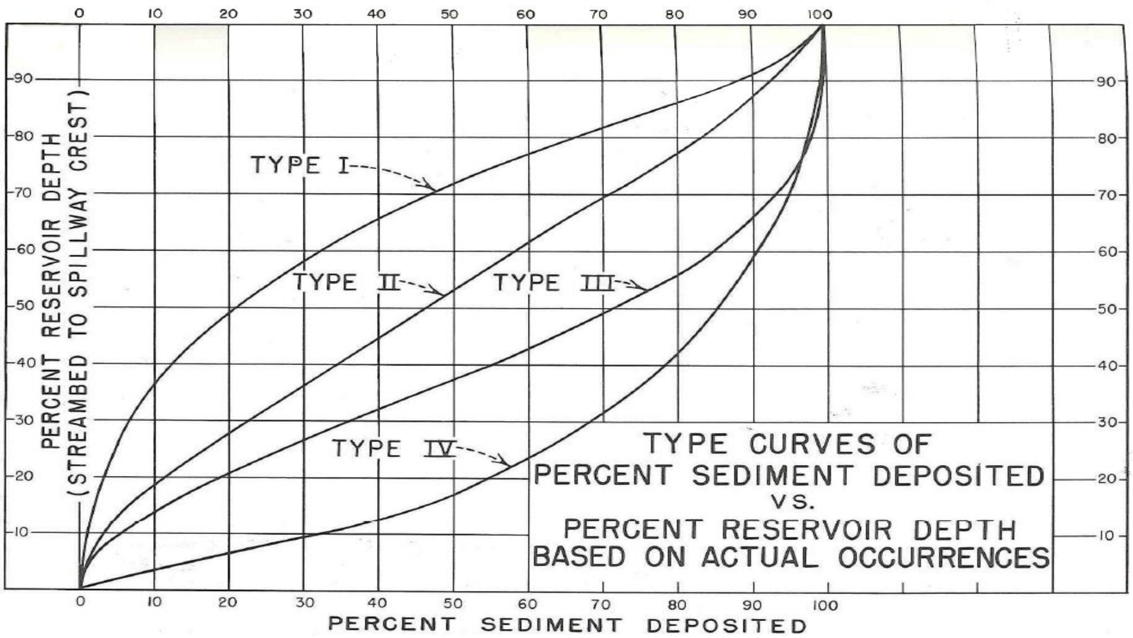


Fig. 4.3 Sediment distribution in different types of reservoirs (reproduced from Borland & Miller 1960)

4.8.2 LH-OAT optimization technique

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) and generating a reasonable sample from a collection of distributed multidimensional field. McKay et al (2000) has compared random, stratified and Latin Hypercube sampling random variables in Monto Carlo studies. 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 space or probability distribution was split into *x* numbers of intervals or probabilities in such a way so that exactly one observation laid 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 LHS keeping other parameters constant to examine all combinations that may prevail in the system.

For determination of sediment profile, the original elevation and capacities were plotted on log-log paper to determine the type and parameters *C, m* and *n* for a 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 was considered for optimization keeping other constants and revised profile of sediments was obtained. A computer program was developed in FORTRAN, where, the parameters *C*, *m*, *n* were changed one-by one and revised profile were determined considering appropriate new zero elevation using trial and error method. For doing this, each time for value of *C*, *m* and *n*, a revised bed level was 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 was computed else next revised level was considered. If the computed revised sediment did not converge with actual sediment, then next combination of *C*, *m* and *n* were used as per LH-OAT sampling and best selection which gave the minimum difference between observed and computed total computed sediment has been selected for that reservoir.

CHAPTER- 5: ANALYSIS OF RESULTS

The digital image classification of remote sensing data has been used to determine revised water spreads which in turn used for estimation of revised capacities and losses at various levels of reservoir. For determination of revised water spreads at regular intervals, seven to nine different remote sensing LISS3 scenes were procured from NRSC, Hydearbad and OLI scenes from LANDSAT were downloaded, imported and geo-referenced with the help of index map/topo-sheets in ARC GIS software. The digital image analysis has been performed to estimate the revised water spread. The normalized deviation water indexes (NDWI), image ratio and then slicing of image classification have been used to differentiate the water pixels from other land uses. The revised water spreads computed in this way were used to estimate revised capacities between the levels and revised gross capacities at different levels of reservoir. The levels of reservoir generally do not go below dead storage level due to revised water spreads and thus capacities below DSL and revised bed level cannot be determined by RS technique. This limitation of RS was overcome by graphical representation of revised water spreads and extending the best-fit curve backward to get revised bed level. The sediment profile of total sediment deposition was computed by conventional empirical area reduction method and LH-OAT optimization based approach for Gondli reservoir in second part of study where data of original E-A-C table was available. The results of estimation of revised capacities, loss in storages and sediment profiling for selected reservoirs are presented below.

5.1 Kharkhara Reservoir

To determine revised capacities of Kharkhara reservoir, eight different remote sensing scenes were analyzed and revised water spreads were computed. The false color composite (FCC), NDWI and extracted water spread for few dates of Kharkhara reservoir have been depicted in Fig. 5.1. As water level seldom goes below dead storage level and some time it is not possible to get a scene on full reservoir level, a scatter graph was plotted between reservoir elevation and revised water spread area and a best-fit curve was fitted to evaluate revised water spreads on these levels. The best-fit curve for revised water spreads suggested that the revised bed of Kharkhara reservoir can be considered as 318.27 m against its original bed as 309.37 m. With the help of revised spread areas, the revised cumulative capacity and percentage loss in cumulative storages at different levels have been estimated and presented in Table 5.2. The graphical representation of original capacities in the year 1967 and revised cumulative capacity in the year 2017 for Kharkhara reservoir has been presented in Fig. 5.2. The result of study suggested that that 8.41 Mm^3 of gross storage has been lost due to deposition of sediment in 51 years (1967 to 2017) and if the uniform rate is considered, the sedimentation in this reservoir comes out to be 0.16 Mm^3/ year. It can also be confirmed that nearly 80% dead storage and 1.5% of live storage of this reservoir have been lost in the last 51 years of operation of reservoir.

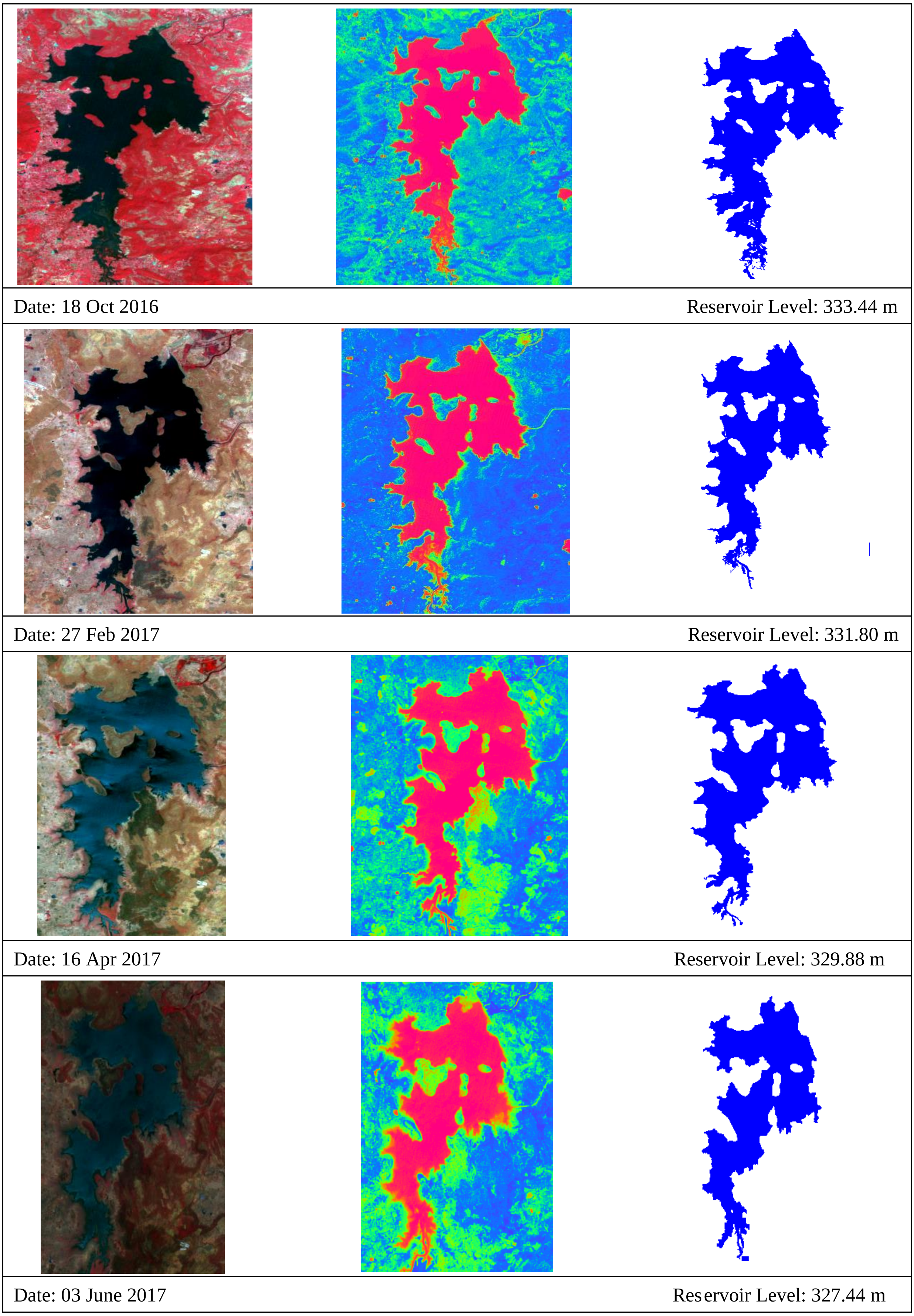


Fig 5.1 FCC, NDWI and extracted water spreads of few dates for Kharkhara reservoir

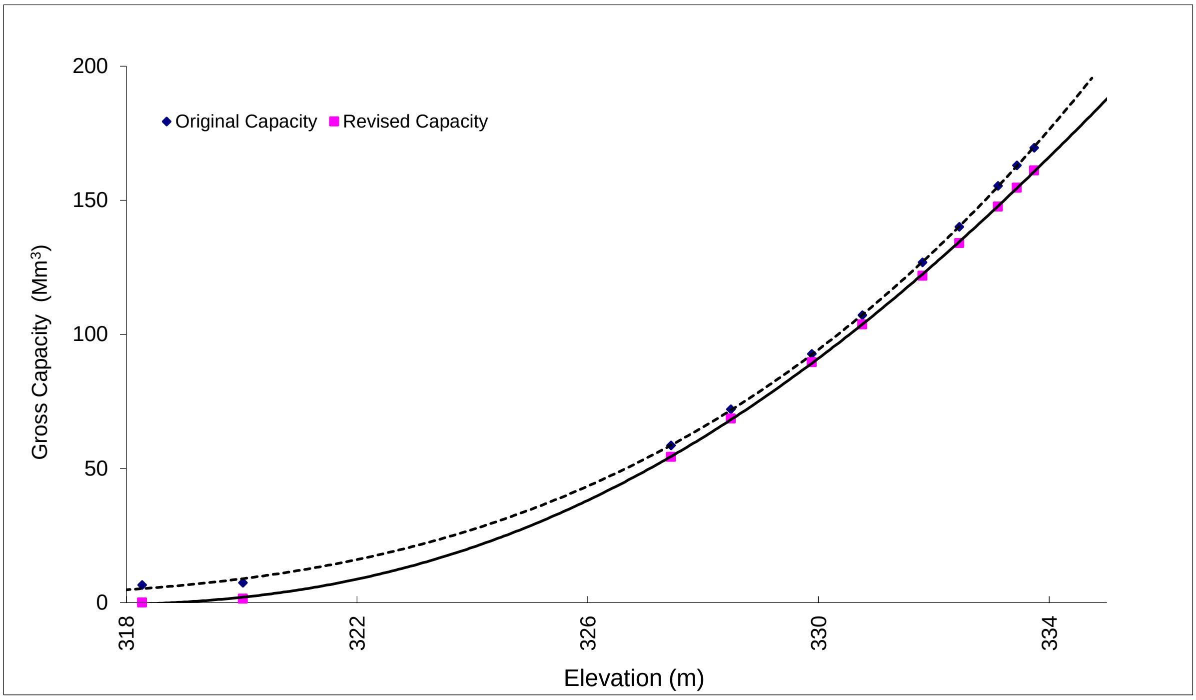
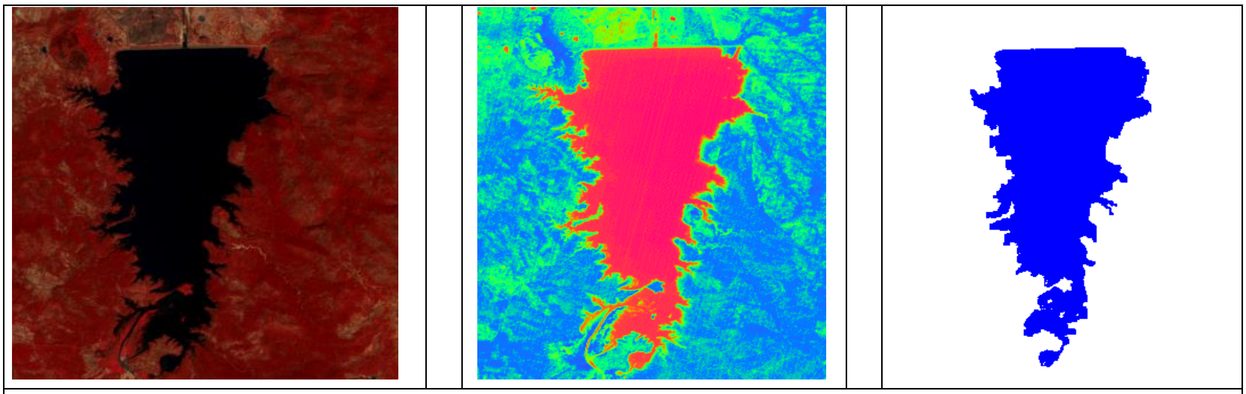


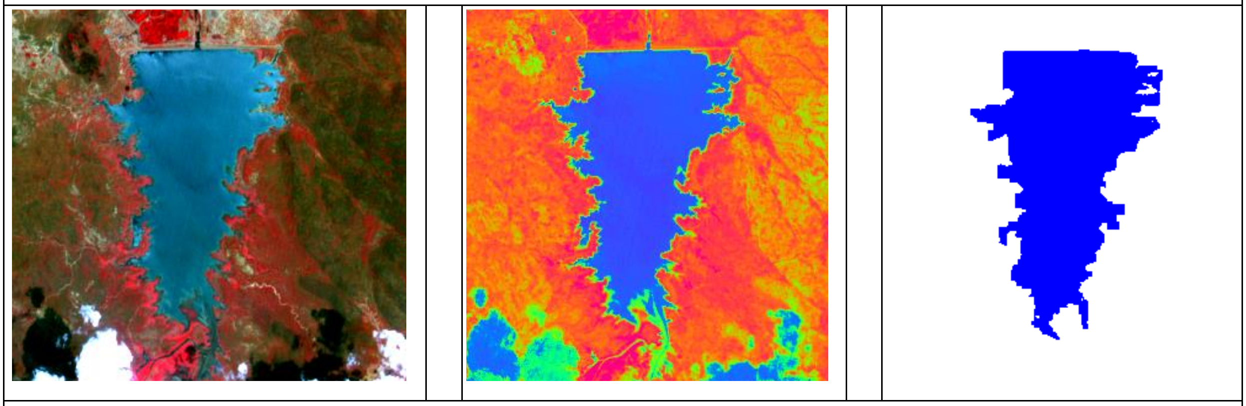
Fig. 5.2 Original and revised cumulative capacity curves for Kharkhara reservoir

5.2 Sondur Reservoir

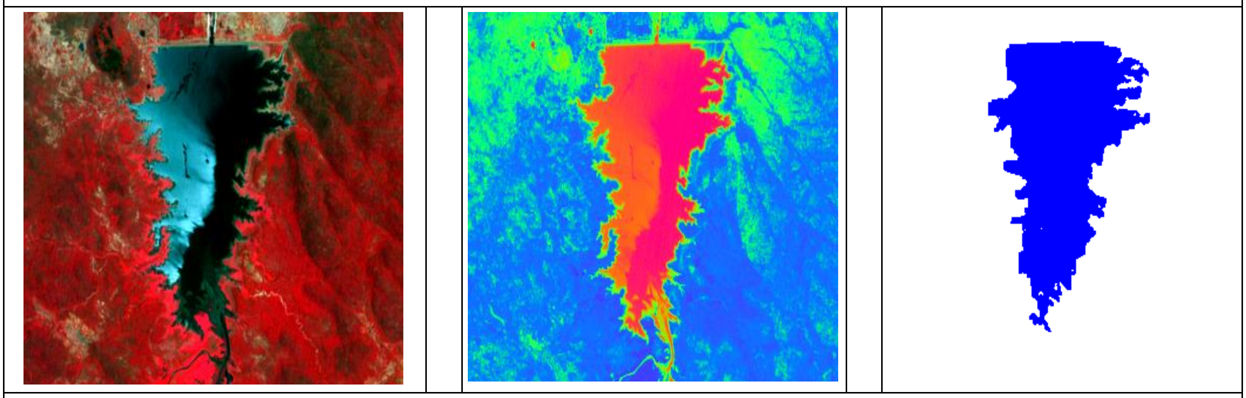
In case of Sondur reservoir, eight temporally varied scenes covering live storage zones were analyzed and revised water spreads were computed. The FCC, NDWI and extracted water spreads at different levels of few dates for Sondur reservoir has been presented in Fig. 5.3. A scatter graph has been plotted between revised water spread and reservoir level and the best-fit curve was extended backward and forward to find out revised bed level and revised water spread at F.S.L. The present bed level found out from analysis is 454.3 m in comparison of actual bed of 447.07 m as given in original capacity table. The original, revised capacities and loss in cumulative capacities of Sondur reservoir has been presented in Table 5.2 and Fig. 5.4. From the analysis, it has been found that 12.45 Mm^3 (6.3%) of gross storage have been lost in 28 years (1988 to 2015) from Sondur reservoir. The rate of deposition in Sondur reservoir may be computed as 0.44 Mm^3/year. The loss in dead storage of Sondur dam is much higher than live storage zone may be due to steep slope towards reservoir. The soil conservation measures should be taken in Sondur reservoir to limit siltation in the reservoir.



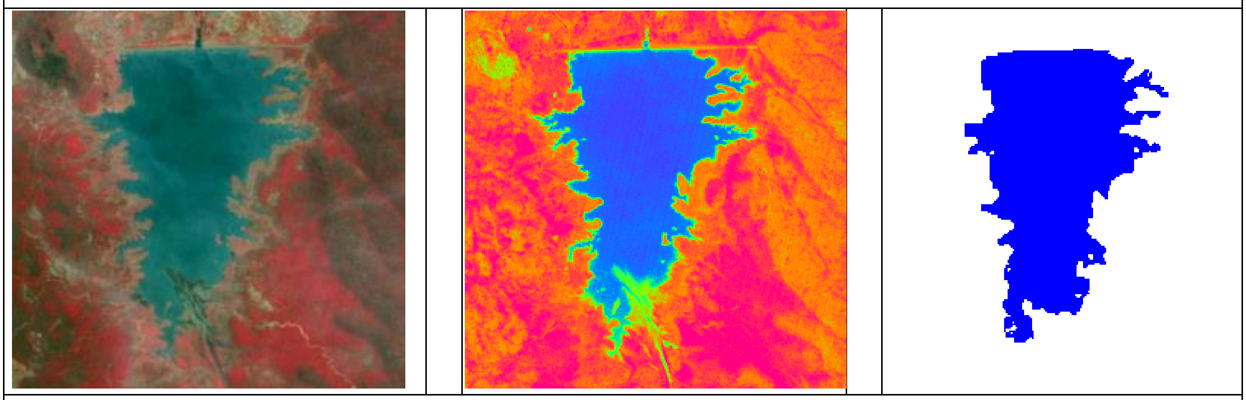
Date : 20 Mar 2014 — Reservoir Level: 467.20 m



Date : 25 Apr 2014 — Reservoir Level: 465.12 m



Date : 14 May 2015 — Reservoir Level: 463.67 m



Date : 12 June 2014 — Reservoir Level: 462.44 m

Fig 5.3 FCC, NDWI and extracted water spreads of few dates for Sondur reservoir

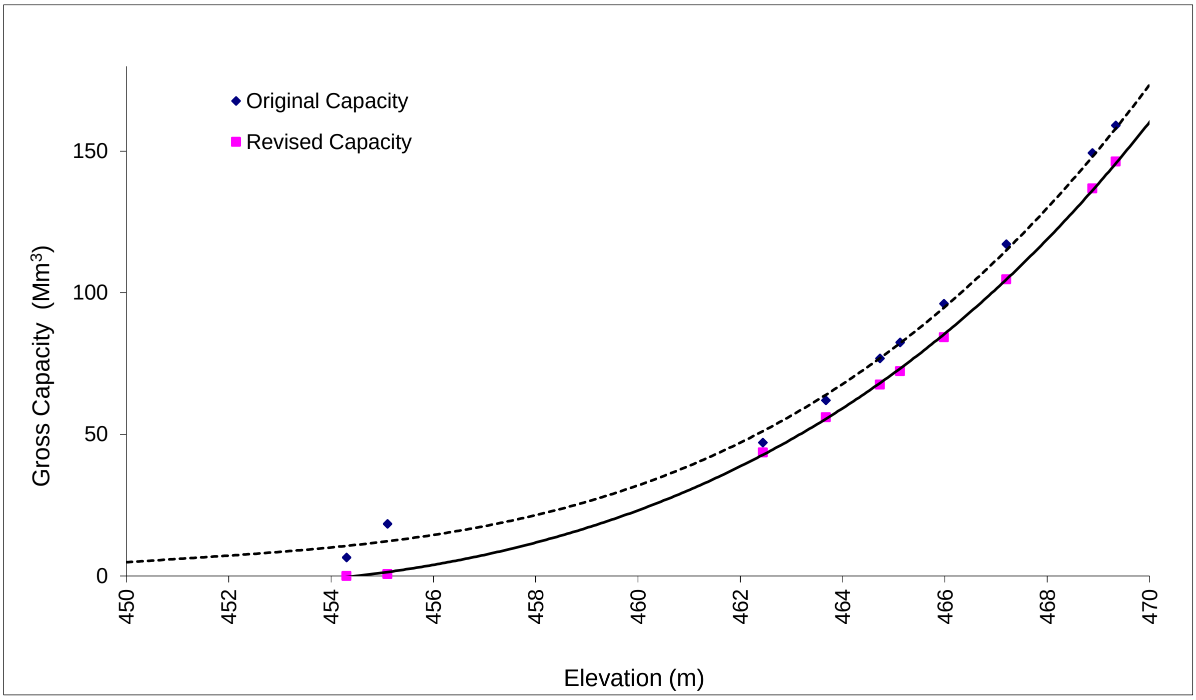
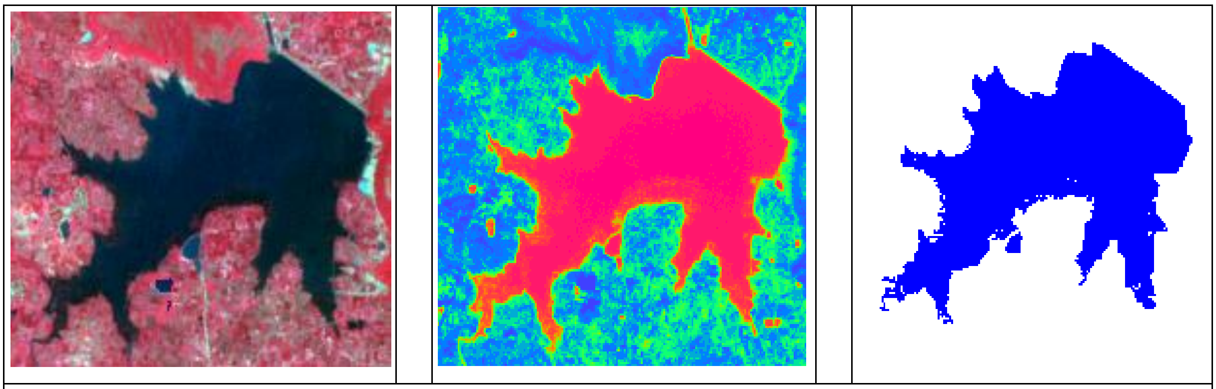


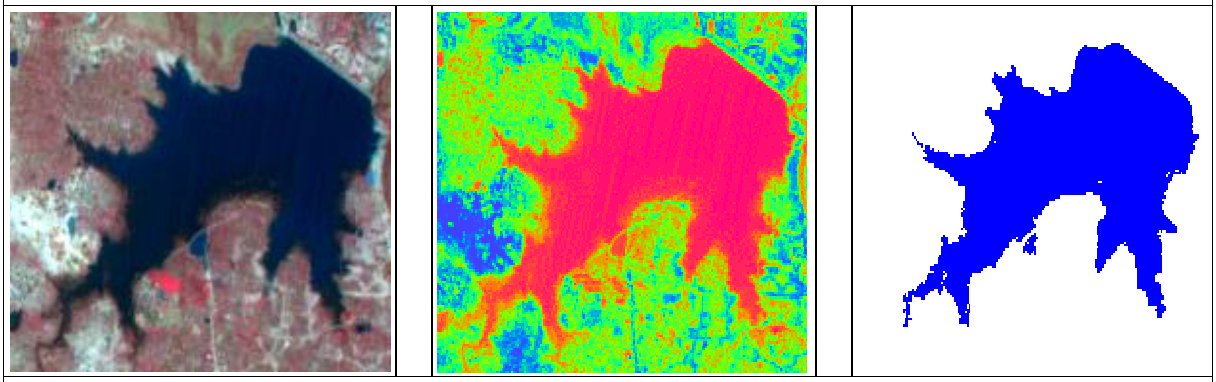
Fig. 5.4 Original and revised cumulative capacity curves for Sondur reservoir

5.3 Matiamoti Reservoir

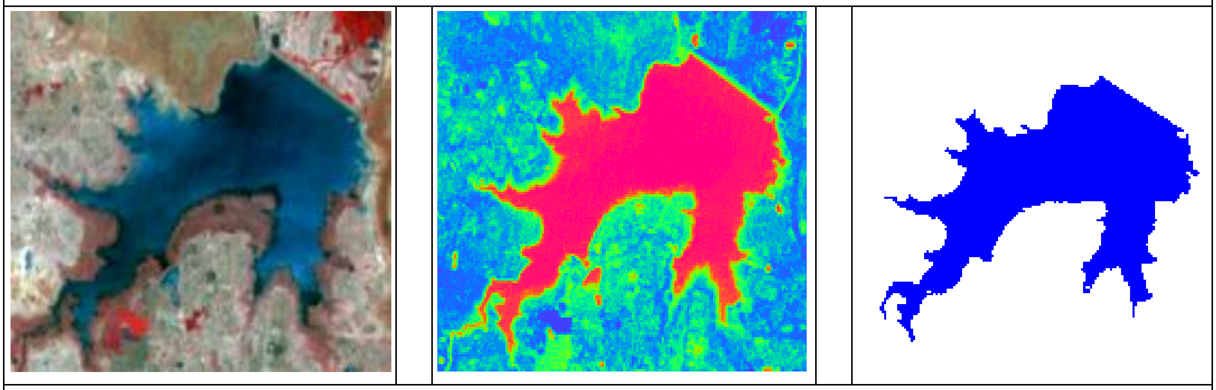
The revised capacity of Matiamoti reservoir was computed using eight different LISS III data covering whole range of live storage. Few FCC, NDWI and extracted water spreads at different reservoir levels of Matiamoti reservoir have been presented in Fig. 5.5. From the analysis of scatter graph plotted between levels and revised water spreads fitted with a smooth curve, it has been found that present river bed at dam site of Matiamoti reservoir can be considered as 319.9 m in place of original bed of 319.07 m. The computation of revised cumulative capacities and loss in gross storages of Matiamoti reservoir has been presented in Table 5.3. The graphical representation of original and revised capacity curve of Matiamoti reservoir is depicted in Fig. 5.6. From the analysis, it has been found that 4.59 Mm^3 (15.5%) of gross storage and 2.36 Mm^3 (79.2%) of dead storage have been lost in 24 years (1994 to 2017) from Matiamoti reservoir. The rate of deposition in Matiamoti reservoir may be computed as 0.19 Mm^3/year. The loss of storages in Matiamoti reservoir is more towards dead storage zone than live storage zone may be due to steep slope towards reservoir. The soil conservation measures should be taken in Matiamoti reservoir to limit siltation in live storage zone.



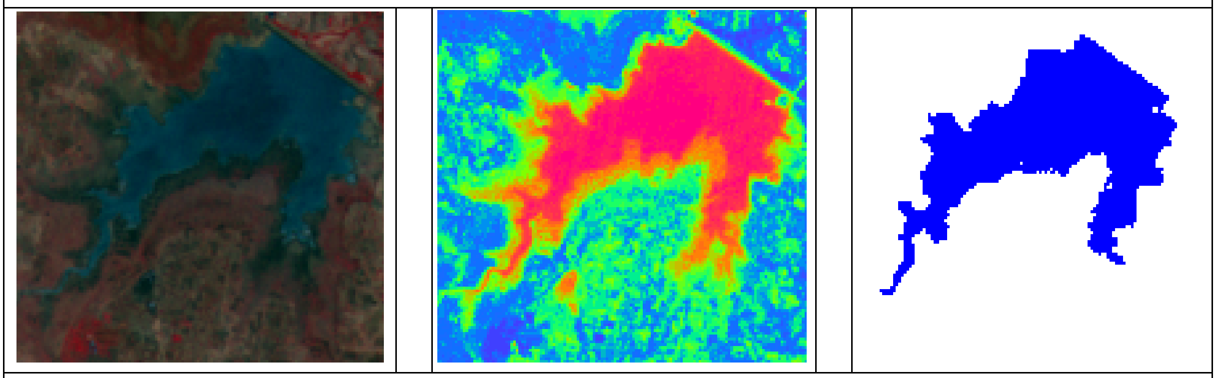
Date : 18 Oct 2016 Reservoir Level: 328.50 m



Date : 03 Feb 2017 Reservoir Level: 327.86 m



Date : 16 Apr 2017 Reservoir Level: 325.75 m



Date : 09 Jun 2017 Reservoir Level: 323.04 m

Fig 5.5 FCC, NDWI and extracted water spreads of few dates for Matiamoti reservoir

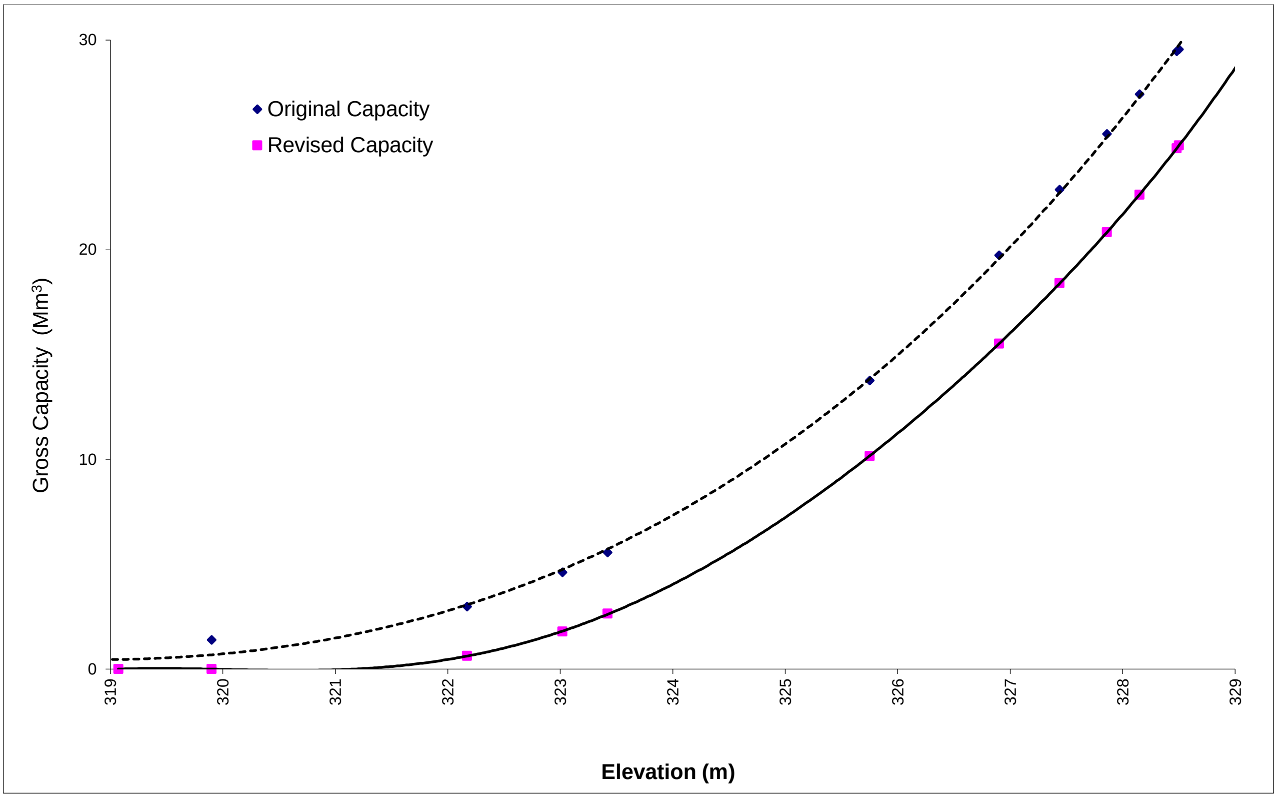


Fig. 5.6 Original and revised cumulative capacity curves for Matiamoti reservoir

5.4 Mongra Reservoir

For estimation of revised capacity of Mongra reservoir, eight different scenes of remote sensing LISS III sensors were imported and digitally processed in GIS software. The FCC, NDWI and extracted water spreads on few levels of Mongra reservoir have been presented in Fig. 5.7. The original bed level of Mongra reservoir was not known and hence computations were made for live storage zone only assuming no loss in dead storage zone due to most of the sediment passes through Mongra barrage during rainy season. The revised cumulative capacities and loss in gross storages has been presented in Table 5.4. The graphical representation of original and revised capacity curve of Mongra reservoir has been presented in Fig. 5.8. The Mongra reservoir has started it operation in 2008 and this assessment has been carried out in the year 2017 that indicated that 3.67 Mm^3 (7.5%) of live storage have been lost due to sediment deposition in ten years. The constant rate of siltation in Mongra reservoir may be about 0.37 Mm^3/year.

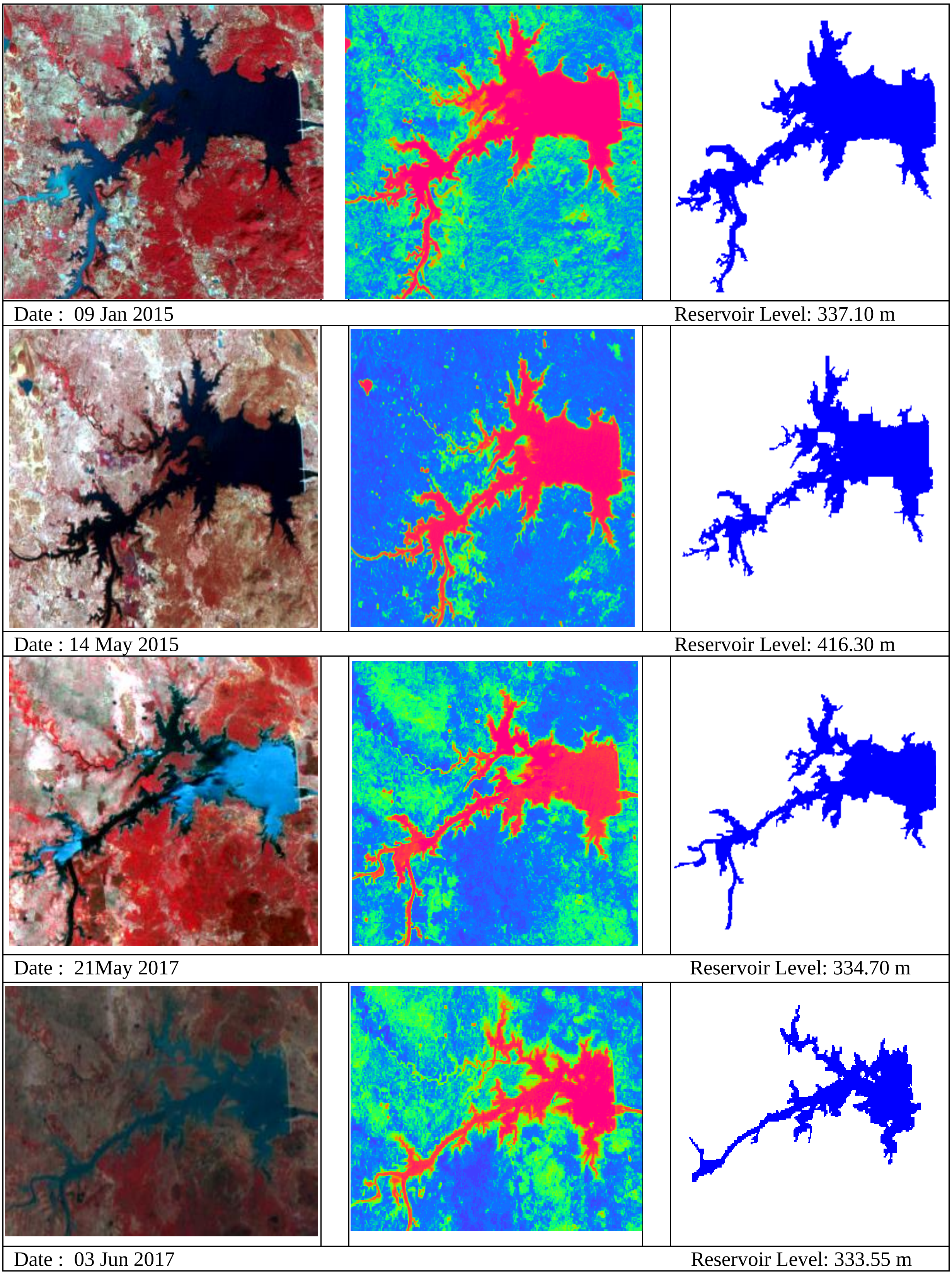


Fig 5.7 FCC, NDWI and extracted water spreads of few dates for Mongra reservoir

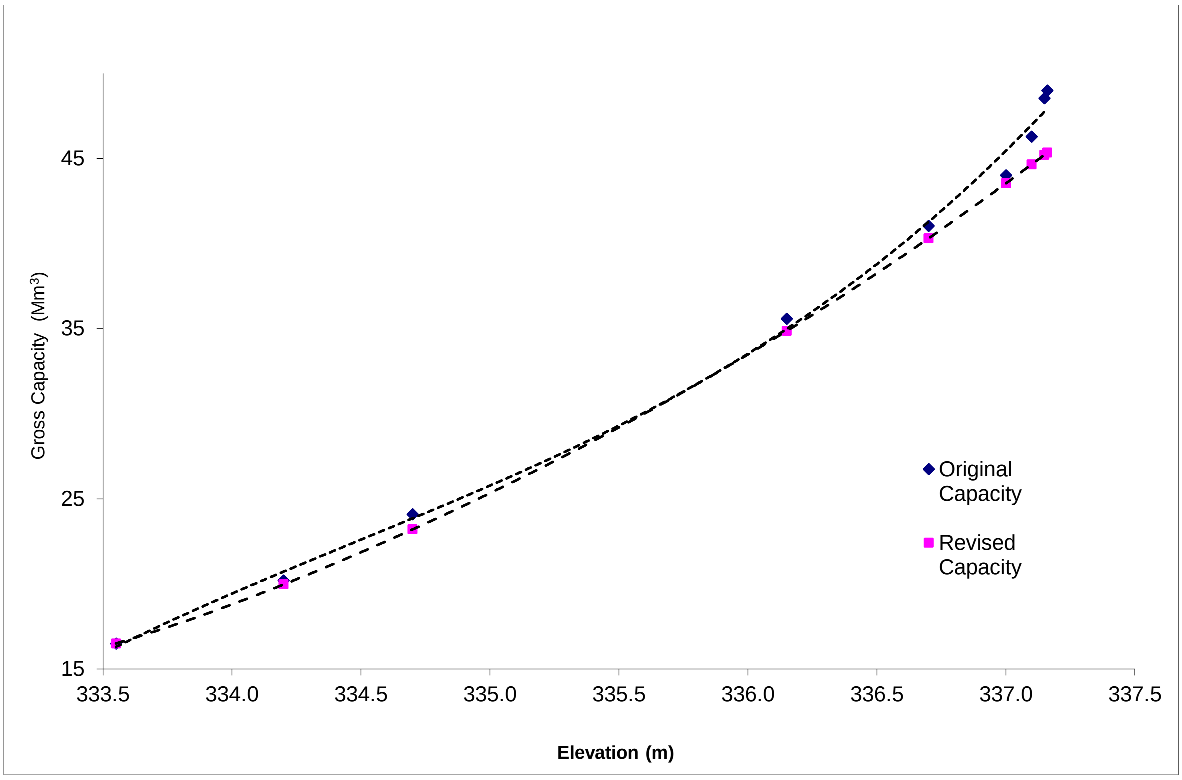


Fig. 5.8 Original and revised live capacity curves for Mongra reservoir

5.5 Paralkot Reservoir

The revised capacity of Paralkot reservoir was computed using eight different scenes of Landsat data covering whole range of live storage. The FCC and extracted water spreads for few levels of Parakot reservoir have been presented in Fig. 5.9. As revised water spreads below dead storage level (DSL) was not available, a scatter graph has been plotted as done for other reservoir between reservoir levels and revised water spreads. A best-fit curve has been plotted and extended below DSL to compute revised water spreads on these levels. From the analysis, it has been found that present river bed at dam site of Paralkot reservoir can be considered as 335.31 m in place of original bed of 327.29 m. It shows that the storage between these two levels has completely lost due to deposit of sediment material brought by the river. The computation of revised cumulative capacities and loss in gross storages has been presented in Table 5.5. The graphical representation of original and revised capacity curve for Paralkot reservoir has been presented in Fig. 5.10. From the analysis, it has been found that 3.53 Mm^3 (5.33%) of gross storage and 2.28 Mm^3 (84.1%) of dead storage have been lost in 37 years (1981 to 2017) from Paralkot reservoir. The rate of deposition in Paralkot reservoir may be computed as 0.10 Mm^3/year if constant rate is considered.

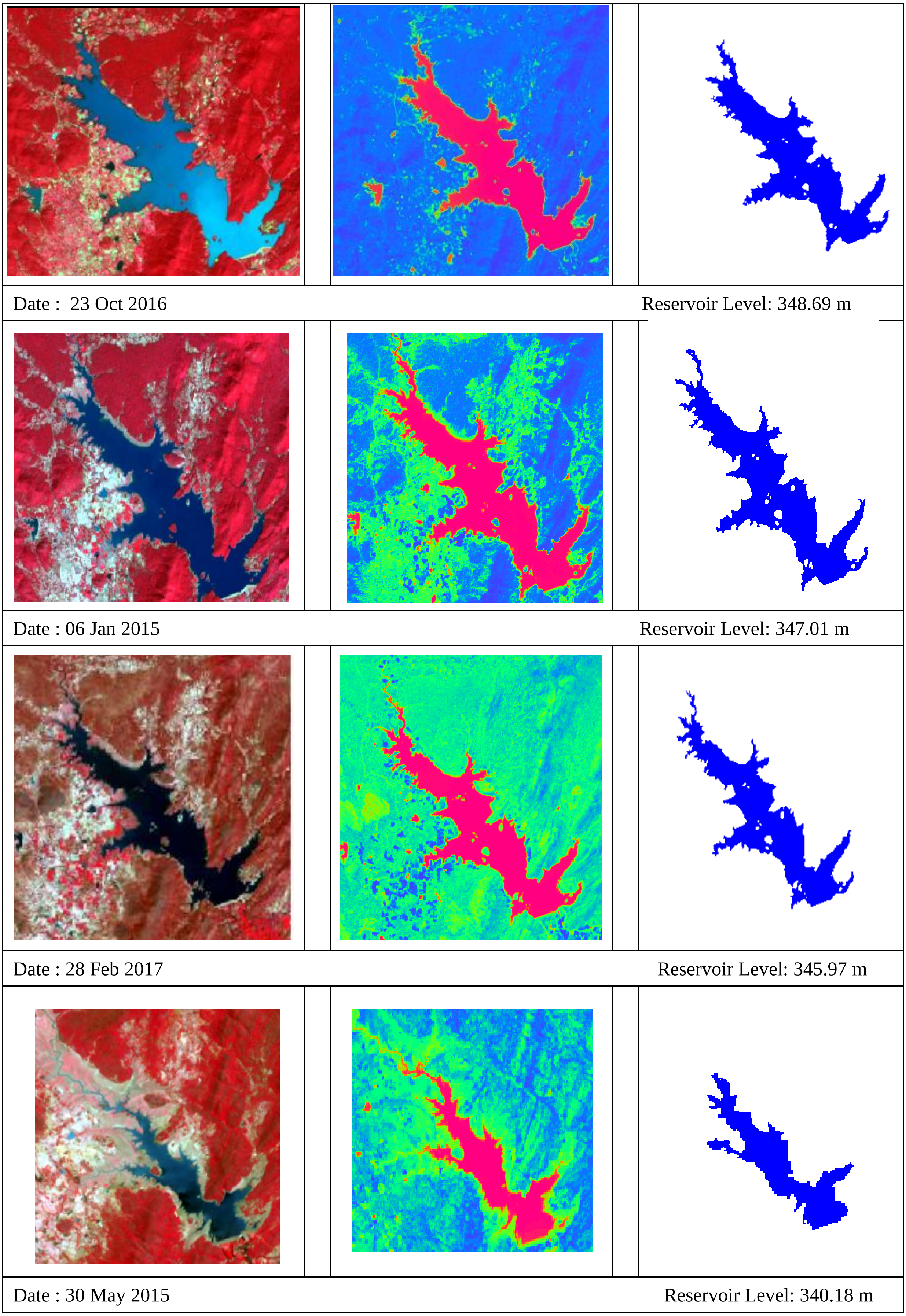


Fig 5.9 FCC, NDWI and extracted water spreads of few dates for Paralkot reservoir

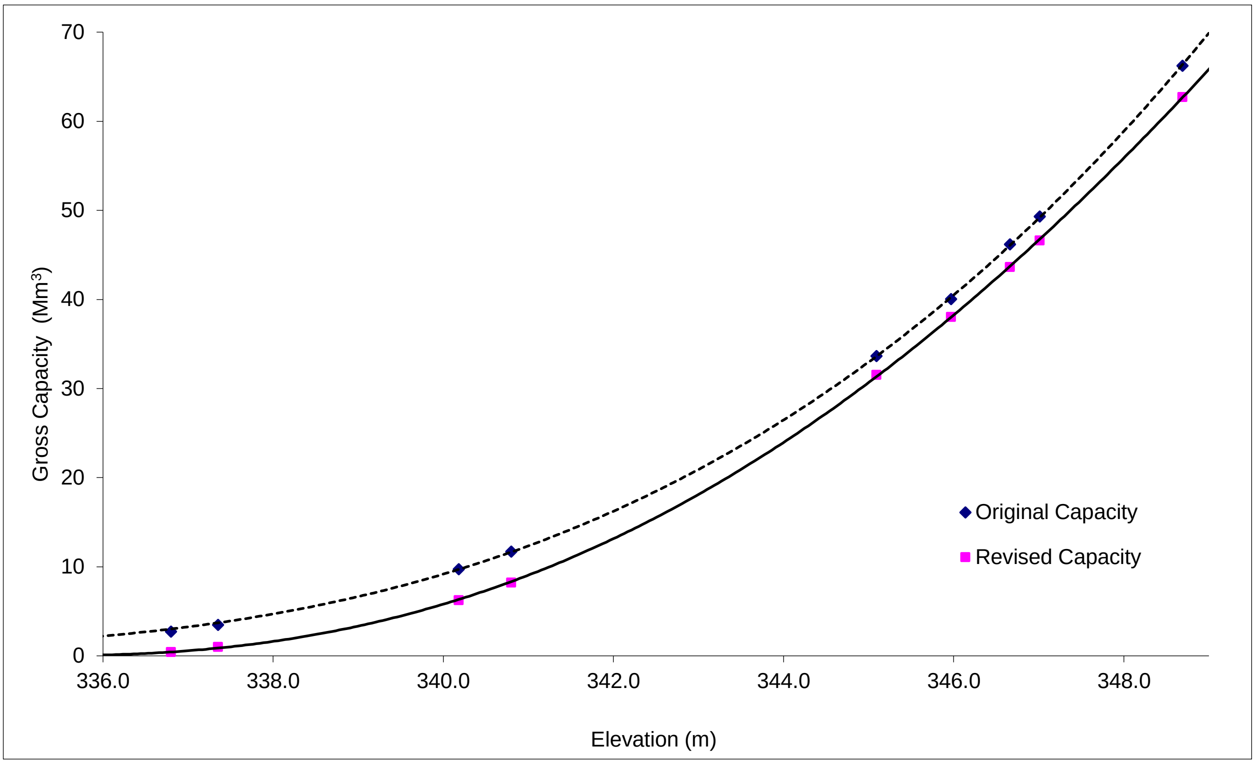


Fig. 5.10 Original and revised cumulative capacity curves for Paralkot reservoir

The glimpses of results obtained from the study of reservoir sedimentation of selected reservoirs are presented in Table 5.6. The rate of sediment in reservoirs considered in the present study were compared with empirical equations given by Khosla and Jogelkar for Indian reservoirs. From the analysis of results of ten reservoirs selected in two years of study, it has been observed that the rate of sediment in reservoirs in upper Mahanadi basin may vary between 0.032 and 0.10 $Mm^3/100\ km^2/yr$. The curves of reservoir sediment rates from Khosla and Jogelkar curves were plotted along with the results of present study and shown in Fig. 5.11. From the analysis, it has been observed that the rates of sediment in the reservoirs of Chhattisgarh follow Khosla's curve more closely and following formula can be used to compute rate of sedimentation based on catchment area during planning purposes.

$$V_s = \frac{0.164}{A^{0.16}} \qquad (5.1)$$

where, V_s is the rate of sedimentation in $Mm^3/100\ km^2/yr$ and A is the catchment area in km^2.

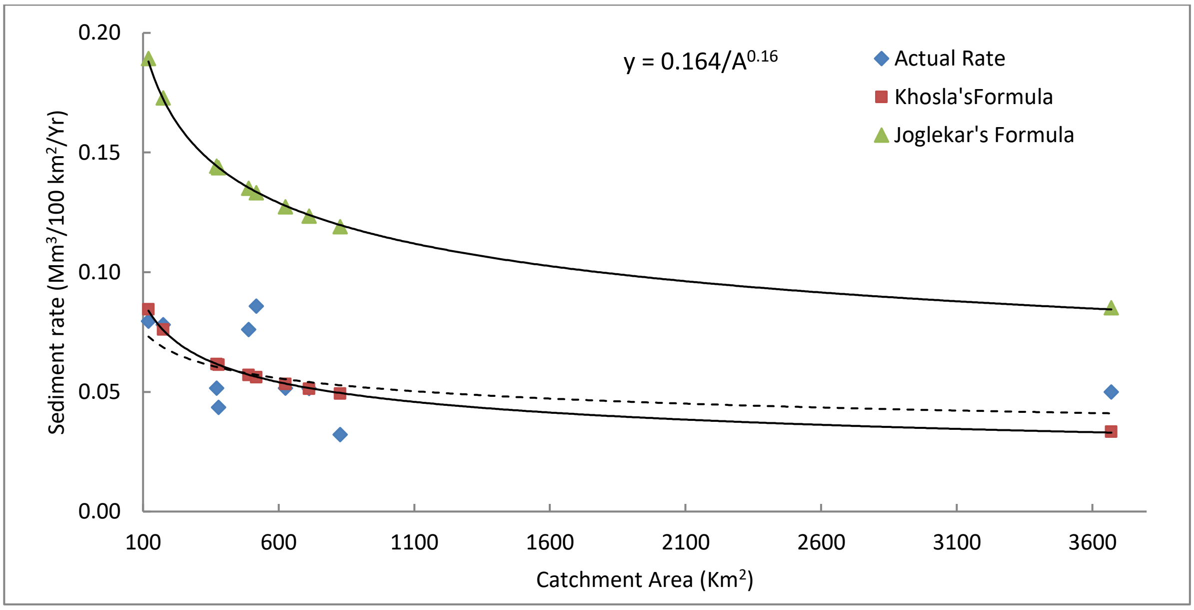


Fig. 5.11 Relation of sediment deposit with catchment characteristics

5.6 Sediment Profiling

For determination of sediment profile of a reservoir by conventional and optimized method, a program in FORTRAN has been developed where original and revised elevation-area-capacity table and total sediment deposit were used as input to the program. The conventional and LH-OAT based optimized *C*, *m* and *n* were determined and subsequently used in determination of revised bed level and total sediment deposited which provided revised capacities at different levels of reservoir. The profile assessment has been carried out for Gondli reservoirs in part-II of study.

5.6.1 Sediment profile for Gondli Reservoir

The developed program was run to determine revised capacities at different levels of Gondli reservoir for deposition of 7.21Mm^3 of sediment. Conventionally, the parameters *C*, *m* and *n* of empirical area reduction method were found out as 3.417, 1.5 and 0.2 respectively indicated that this reservoir is Type IV reservoir which means foothill reservoir. The revised bed obtained for this sediment deposit was 332.08 m. The program when run with LH-OAT optimization, the values of *C*, *m* and *n* were find out as 6.4, 3.6 and 2.6. The revised bed found out as 332.72 m which is close to the revised river bed (332.80 m) obtained from remote sensing analysis proved that the approach of back ward extension of revised water spread curve can be used to find out revised river bed. The revised cumulative capacity curve obtained from remote sensing analysis, conventional and optimized empirical area reduction method has been depicted in Fig. 5.12 clearly indicated close match proved use of back ward extension of revised water spread curve in dead storage zone to determine revised river bed level in remote sensing method.

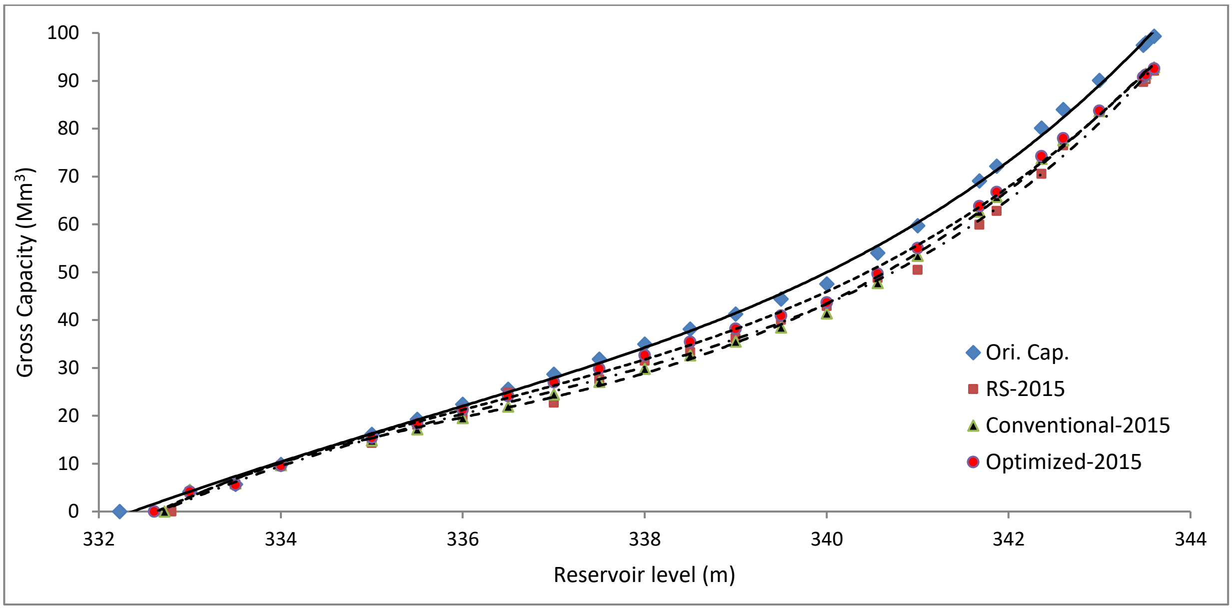


Fig. 5.12 Original and revised capacity curves from RS, Conventional and optimized techniques for Gondli reservoir

CHAPTER- 6: CONCLUSIONS

The systematic and scientific analysis of catchment and command areas may be helpful in planning to reduce distribution losses, equitable distribution of water and increase in crop yields which lead to overall livelihood in the region. In the part-II of reservoir sedimentation study, the reservoir sedimentation from four reservoirs in Mahanadi and one from Godavari basin of Chhattisgarh state have been determined by estimation of revised capacity using digital image analysis of remote sensing data. The revised capacities at different levels were estimated for Kharkhara, Sondur, Matiamoti, Mongra and Paralkot reservoirs. The multi-temporal LISS 3 data were used in the analysis to cover whole live storage range in approximately equal intervals. The revised water spreads obtained from digital image processing were used to compute revised storage and cumulative capacities at different levels.

The analysis suggested that the 8.41 Mm^3 from 169.54 Mm^3 of gross storage of Kharkhara reservoir has been lost due to deposition of sediment in 51 years (1967 to 2017). The rate sediment in this reservoir may be about 4.36 ha-m/100 km^2/year.

The Sondur reservoir, an important reservoir in Ravishankar Sagar complex system in Chhattisgarh has lost 12.45 Mm^3 from original 198.1 Mm^3 of gross storage in 28 years (1988 to 2015). The rate of sediment in Sondur reservoir may be about 8.58 ha-m/100 km^2/yr.

The revised capacity assessment of Matiamoti reservoir concluded that 2.36 Mm^3 of dead storage and 4.63 Mm^3 of gross storage have lost in 24 years (1994 to 2017). The rate of sediment in Matiamoti reservoir may be about 5.12 ha-m/100 km^2/yr.

Mongra barrage started its operation in the year 2008 and up to 2017 and considering its releases of all the sediment laden water of monsoon through its opening, the estimation has been made for live storage zone only. From the analysis, it has been observed that 7.48 Mm^3 of storage from total storage of 49 Mm^3 has been lost in 10 years. The rate of sediment in Mongra reservoir may be about 5.15 ha-m/100 km^2/yr.

Paralkot reservoir situated in Godavari basin started its operation in 1981 during this period (1981 to 2017), nearly 3.53 Mm^3 gross storage from 66.25 Mm^3 has been lost. The rate of sediment in Paralkot reservoir may be about 7.96 ha-m/100 km^2/yr.

The study of ten different reservoirs from both years of study suggested that rate of sedimentation found close resemblance with Khosla's formula and a new equation has been suggested to find out rate of sedimentation in the region. The loss of capacity in reservoir from all the reservoirs considered in two years of study varied from 0.10 Mm^3/year in Paralkot reservoir to 1.87 Mm^3/year in Ravishankar Sagar reservoir. The sediment profile of Gondli reservoirs were determined using empirical area reduction method where parameters *C*, *m* and *n* were computed conventional and LH-OAT based optimization techniques in this two year study. The river bed obtained from optimization technique was found close to method of back ward extension of best fitted curve of revised water spreads obtained from remote sensing approach. This implies the use of best fit curve of revised water spreads for determination of revised bed level.

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TABLES

Table 3.1 The original elevation-area-capacity Table of Kharkhara reservoir

S.N.	Elevation (m)	Area (km^2)	Capacity (M. m^3)
1.	309.41	0.00	0.00
2.	320.08	566.56	7.45
3.	320.94	634.55	10.56
4.	321.85	707.39	14.16
5.	322.03	721.96	14.98
6.	322.83	785.09	19.11
7.	323.41	845.79	22.40
8.	324.41	979.34	29.02
9.	324.75	1023.85	31.32
10.	325.42	1112.89	36.67
11.	326.00	1189.78	42.08
12.	327.00	1323.32	53.24
13.	327.40	1375.93	57.62
14.	329.01	1590.41	78.61
15.	330.02	1759.03	94.21
16.	331.00	1931.70	110.63
17.	332.00	2109.76	129.83
18.	333.01	2287.82	151.86
19.	334.01	2503.66	175.25
20.	334.50	2676.32	187.63
21.	335.32	3156.55	208.41

Table 3.2 The original elevation- capacity Table of Sondur reservoir

S.N.	Elevation (m)	Capacity (M. m^3)
1.	447.1	0.0
2.	450.0	2.0
3.	455.0	6.0
4.	457.0	10.0
5.	459.1	17.0
6.	460.0	23.9
7.	461.0	32.4
8.	462.0	42.3
9.	463.0	53.5
10.	464.0	66.4
11.	465.0	80.7
12.	466.0	96.4
13.	467.0	113.6
14.	468.0	132.0
15.	469.0	151.9
16.	470.0	173.4
17.	471.0	196.6
18.	472.0	221.6
19.	472.1	222.0

Table 3.3 The original elevation-area-capacity Table of Mongra reservoir

S.N.	Elevation (m)	Capacity (M. m^3)
1.	333.5	0
2.	334.0	2.5
3.	334.5	5.0
4.	335.0	7.5
5.	335.5	12.5
6.	336.0	17.5
7.	336.5	22.5
8.	337.0	27.5
9.	337.15	32.0

Table 3.4 The original elevation-capacity Table of Matiamoti reservoir

S.N.	Elevation (m)	Capacity (M. m^3)
1.	322.17	2.98
2.	322.5	3.55
3.	323	4.57
4.	323.5	5.76
5.	324	7.16
6.	324.5	8.78
7.	325	10.58
8.	325.5	12.6
9.	326	14.99
10.	326.5	17.53
11.	327	20.29
12.	327.5	23.24
13.	328	26.52
14.	328.3	28.32
15.	328.48	29.46

Table 3.5 Original elevation-capacity table of Paralkot reservoir

S.N.	Elevation (m)	Capacity (Mm3)
1.	323.7	0.0
2.	333.6	16.5
3.	334.0	18.7
4.	334.5	22.6
5.	334.7	24.1
6.	335.0	26.4
7.	335.3	28.7
8.	335.5	30.3
9.	335.7	31.8
10.	336.0	34.1
11.	336.3	37.1
12.	336.5	39.1
13.	336.7	41.0
14.	337.0	44.0
15.	337.1	46.3
16.	337.2	48.6

Table 3.6 (a) Remote sensing data used for Kharkhara Sagar reservoir

S.N.	Date of pass	Elevation (m)	Path/Row	Satellite	Sensor
1	03-Jun-17	327.44	101/57	IRS-P6	LISS-III
2	21-May-15	328.48	101/57	IRS-P6	LISS-III
3	16-Apr-17	329.88	101/57	IRS-P6	LISS-III
4	23-Mar-17	330.76	101/57	IRS-P6	LISS-III
5	27-Feb-17	331.80	101/57	IRS-P6	LISS-III
6	03-Feb-17	332.44	101/57	IRS-P6	LISS-III
7	09-Jan-15	333.11	101/57	IRS-RS2	LISS-III
8	18-Oct-16	333.44	101/57	IRS-RS2	LISS-III

Table 3.6 (b) Remote sensing data used for Sondur reservoir

S.N.	Date of pass	Elevation (m)	Path/Row	Satellite	Sensor
1	12-Jun-14	462.44	102/58	IRS-P6	LISS-III
2	14-May-15	463.67	102/58	IRS-1D	LISS-III
3	02-May-15	464.73	102/58	IRS-P6	LISS-III
4	25-Apr-14	465.12	102/58	IRS-1D	LISS-III
5	20-Apr-15	465.98	102/58	IRS-1D	LISS-III
6	20-Mar-14	467.20	102/58	IRS-P6	LISS-III
7	15-Mar-15	468.88	102/58	IRS-1D	LISS-III
8	08-Nov-13	469.34	102/58	IRS-1D	LISS-III

Table 3.6 (c) Remote sensing data used for Mongra reservoir

S.N.	Date of pass	Elevation (m)	Path/Row	Satellite	Sensor
1	03-Jun-17	333.55	101/57	IRS-P6	LISS-III
2	16-Apr-17	334.20	101/57	IRS-P6	LISS-III
3	21-May-17	334.70	101/57	IRS-P6	LISS-III
4	23-Mar-17	336.15	101/57	IRS-P6	LISS-III
5	27-Feb-17	336.70	101/57	IRS-P6	LISS-III
6	03-Feb-17	337.00	101/57	IRS-P6	LISS-III
7	09-Jan-15	337.10	101/57	IRS-RS2	LISS-III
8	18-Oct-16	337.16	101/57	IRS-RS2	LISS-III

Table 3.6 (d) Remote sensing data used for Matiamoti reservoir

S.N.	Date of pass	Elevation (m)	Path/Row	Satellite	Sensor
1	03-Jun-17	323.02	101/57	IRS-P6	LISS-III
2	21-May-15	323.42	101/57	IRS-P6	LISS-III
3	16-Apr-17	325.75	101/57	IRS-P6	LISS-III
4	23-Mar-17	326.90	101/57	IRS-P6	LISS-III
5	27-Feb-17	327.44	101/57	IRS-P6	LISS-III
6	03-Feb-17	327.86	101/57	IRS-P6	LISS-III
7	09-Jan-15	328.15	101/57	IRS-RS2	LISS-III
8	18-Oct-16	328.50	101/57	IRS-RS2	LISS-III

Table 3.6 (e) Remote sensing data used for Paralkot reservoir

S.N.	Date of pass	Elevation (m)	Path/Row	Satellite	Sensor
1	03-Jun-17	337.35	146/43	Landsat8	OLI
2	30-May-15	340.18	146/43	Landsat8	OLI
3	17-Apr-17	340.80	146/43	Landsat8	OLI
4	16-Mar-17	345.09	146/43	Landsat8	OLI
5	28-Feb-17	345.97	146/43	Landsat8	OLI
6	12-Feb-17	346.66	146/43	Landsat8	OLI
7	06-Jan-15	347.01	146/43	Landsat8	OLI
8	23/10/2016	348.69	146/43	Landsat8	OLI

OLI: operational land image

Table 4.1 Classification of reservoir and constant *C*, *m* and *n* (Borland and Miller, 1960)

Reciprocal of slope (m)	Reservoir type	Standard Classification	*C*	*m*	*n*
1.0 to 1.5	Gorge	IV	3.1470	1.5	0.2
1.5 to 2.5	Foothill	III	2.3240	0.5	0.4
2.5 to 3.5	Flood Plain	II	15.882	1.1	2.3
3.5 to 4.5	Lake	I	4.2324	0.1	2.5

Table 5.1 Original, revised capacities and loss in storages of Kharkhara reservoir

Date of Pass	Reservoir Elevation (meter)	Original Capacity (Mm^3)		Revised Capacity (M cu. m)		Loss in Cum. Capacity (Mm^3)	% Loss in Cumulative Capacity
		Volume	Cumulative Capacity	Volume	Cumulative Capacity		
River bed	309.37		0.000		0.000		
Revised Bed*	318.27	6.54	6.54	0.000	0.000	6.54	100.00
DSL	320.02	0.89	7.43	1.41	1.41	6.02	80.99
03-Jun-17	327.44	51.21	58.64	52.88	54.29	4.35	7.42
21-May-15	328.48	13.45	72.09	14.37	68.66	3.43	4.76
16-Apr-17	329.88	20.64	92.73	20.92	89.58	3.15	3.40
23-Mar-17	330.76	14.39	107.12	14.17	103.74	3.38	3.15
27-Feb-17	331.80	19.79	126.92	18.12	121.87	5.05	3.98
03-Feb-17	332.44	13.25	140.17	12.13	133.99	6.17	4.40
09-Jan-15	333.11	15.18	155.35	13.69	147.68	7.66	4.93
18-Oct-16	333.44	7.65	162.99	7.02	154.71	8.28	5.08
FSL *	333.74	6.55	169.54	6.43	161.13	8.41	4.96

Table 5.2 Original, revised capacities and loss in storages of Sondur reservoir

Date of Pass	Reservoir Elevation (meter)	Original Capacity (Mm^3)		Revised Capacity (Mm^3)		Loss in Cum. Capacity	% Loss in Cumulative Capacity
		Volume	Cum. Capacity	Volume	Cum. capacity		
River bed	447.07		0.00		0.00		
Revised Bed*	454.30	6.54	6.54	0.00	0.00	6.54	100.00
DSL	455.10	11.95	18.49	0.75	0.75	17.74	95.92
12-Jun-14	462.44	28.68	47.17	42.94	43.70	3.47	7.36
14-May-15	463.67	14.94	62.11	12.41	56.10	6.01	9.67
02-May-15	464.73	14.74	76.85	11.50	67.61	9.24	12.03
25-Apr-14	465.12	5.70	82.55	4.70	72.31	10.24	12.41
20-Apr-15	465.98	13.60	96.15	12.03	84.34	11.81	12.28
20-Mar-14	467.20	21.08	117.23	20.39	104.74	12.49	10.66
15-Mar-15	468.88	32.23	149.46	32.12	136.85	12.61	8.44
08-Nov-13	469.34	9.64	159.10	9.53	146.38	12.72	7.99
FSL *	471.07	39.00	198.10	39.26	185.65	12.45	6.29

Table 5.3 Original, revised capacities and loss in storages of Mongra reservoir

Date of Pass	Reservoir Elevation (meter)	Original Capacity (M cu. m)		Revised Capacity (M cu. m)		Loss in Cum. Capacity (M cu.m)	% Loss in Cumulative Capacity
		Volume	Cumulative Capacity	Volume	Cumulative Capacity		
03-Jun-17	333.55	16.50	16.50	16.50	16.50	0.00	0.00
16-Apr-17	334.20	3.70	20.20	3.47	19.97	0.23	1.15
21-May-17	334.70	3.89	24.09	3.24	23.20	0.89	3.68
23-Mar-17	336.15	11.50	35.59	11.66	34.86	0.73	2.04
27-Feb-17	336.70	5.44	41.03	5.44	40.30	0.73	1.78
03-Feb-17	337.00	2.97	44.00	3.24	43.54	0.46	1.05
09-Jan-15	337.10	2.28	46.28	1.11	44.65	1.63	3.53
FSL*	337.15	2.27	48.55	0.57	45.22	3.33	6.86
18-Oct-16	337.16	0.45	49.00	0.12	45.33	3.67	7.48

Table 5.4 Original, revised capacities and loss in storages of Matiamoti reservoir

Date of Pass	Reservoir Elevation (meter)	Original Capacity (Mm^3)		Revised Capacity (Mm^3)		Loss in Cum. Capacity (Mm^3)	% Loss in Cumulative Capacity
		Volume	Cumulative Capacity	Volume	Cumulative Capacity		
River bed	319.07		0.00		0.00	-	-
Revised Bed*	319.90	1.39	1.39	0.00	0.00	1.39	100.00
DSL	322.17	1.59	2.98	0.62	0.62	2.36	79.16
03-Jun-17	323.02	1.64	4.62	1.17	1.79	2.83	61.29
21-May-15	323.42	0.94	5.56	0.85	2.64	2.92	52.56
16-Apr-17	325.75	8.21	13.77	7.52	10.16	3.61	26.25
23-Mar-17	326.90	5.96	19.73	5.37	15.53	4.21	21.31
27-Feb-17	327.44	3.14	22.87	2.88	18.40	4.47	19.54
03-Feb-17	327.86	2.65	25.52	2.43	20.83	4.69	18.38
09-Jan-15	328.15	1.90	27.42	1.79	22.62	4.80	17.50
FSL	328.48	2.04	29.46	2.21	24.83	4.63	15.71
18-Oct-16	328.50	0.10	29.56	0.14	24.97	4.59	15.52

Table 5.5 Original, revised capacities and loss in storages of Paralkot reservoir

Date of Pass	Reservoir Elevation (meter)	Original Capacity (Mm^3)		Revised Capacity (Mm^3)		Loss in Cum. Capacity (Mm^3)	% Loss in Cumulative Capacity
		Volume	Cumulative Capacity	Volume	Cumulative Capacity		
River bed	327.29		0.00		0.00		
Revised Bed*	335.31	2.15	2.15	0.00	0.00	2.15	100.00
DSL	336.80	0.57	2.72	0.43	0.43	2.28	84.01
03-Jun-17	337.35	0.75	3.47	0.59	1.03	2.44	70.42
30-May-15	340.18	6.28	9.75	5.23	6.25	3.49	35.83
17-Apr-17	340.80	1.98	11.73	1.99	8.24	3.49	29.73
16-Mar-17	345.09	21.92	33.65	23.29	31.53	2.12	6.29
28-Feb-17	345.97	6.42	40.06	6.51	38.04	2.03	5.06
12-Feb-17	346.66	6.14	46.20	5.59	43.63	2.57	5.56
06-Jan-15	347.01	3.11	49.32	3.00	46.63	2.69	5.45
FSL 23-Oct 2016	348.69	16.935	66.250	16.09	62.716	3.534	5.33

Table 5.6 Glimpses of sediment study results from different reservoirs in Chhattisgarh

Particulars	Reservoir				
	Kharkhara	Sondur	Matiamoti	Mongra	Paralkot
Intercepted Catchment Area (km^2)	378.3	518	371	712.25	120
Year of Impoundment	1967	1988	1994	2008	1981
Year of Survey	2017	2015	2017	2017	2017
Dead Storage Level (meter)	320.02	455.1	322.17	333.55	336.80
Full Supply Level (meter)	333.74	471.07	328.48	337.15	348.69
Original Bed Level (meter)	309.37	447.07	319.07	-	327.29
Revised Bed 2015/2017 (meter)	318.27	454.3	319.9	-	335.31
Original Cumulative Capacity	169.54	198.10	29.56	48.55	66.25
Revised Cumulative Capacity 2015/2017	161.13	185.65	24.97	45.33	62.72
Loss in Gross storage (Mm^3)	8.41	12.45	4.59	3.67	3.53
Rate of Sediment (Mm^3/yr)	0.16	0.44	0.19	0.37	0.10
Rate (ha-m/100 km^2/yr)	4.36	8.58	5.15	5.15	7.96
Rate (Mm^3/100 km^2/yr	0.04	0.09	0.05	0.05	0.08
Rate from Khosla's formula (Mm^3/100 km^2/yr	0.06	0.06	0.06	0.05	0.09
Rate from Joglekar's formula (Mm^3/100 km^2/yr)	0.14	0.13	0.14	0.12	0.19

Director	:	Dr. Sharad K. Jain
Coordinator	:	Dr. N. C. Ghosh
Head	:	Dr. T. R. Nayak

STUDY GROUP

National Institute of Hydrology, Central India Hydrology Regional Centre Bhopal (M.P.)

Sh. R. K. Jaiswal
Dr. T. R. Nayak
Sh. R. V. Galkate
Sh. T. Thomas
Smt. Sashi P. Indwar

State Water Data Centre, WRD, Chhattisgarh (C.G.)

Er. Akhilesh Verma
Er. Rishi Chandrakar
Er. J. N. Vishwakarma
Er. S. K. Verma
Er. S. K. Shukla
Er. T. L. Chandrakar