



उपग्रह दूरस्थ संवेदन द्वारा
भंडारदरा जलाशय, महाराष्ट्र का अवसादन आंकलन

**Sedimentation Assessment of Bhandardara Reservoir,
Maharashtra, through Satellite Remote Sensing**



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SEPTEMBER 2020



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FOREWORD

Sedimentation is a byproduct of erosion in the catchment area of the reservoir and therefore, lesser the rate of erosion, smaller is the sediment load entering the reservoir. Type of soil, drainage density, vegetation, rainfall intensity and duration, shape of the catchment and land use/land cover affect the erosion. Deposition of silt takes place in various parts of reservoir which gradually reduces its capacity. Dead storage capacity as well as live storage capacity gets affected due to siltation. Information about reduction in the storage capacity is necessary for the planning and operational purposes. In some of the reservoirs, the rate of siltation has been higher than what was considered at the planning stage. Therefore, it has become necessary to conduct surveys in all the existing reservoirs for ascertaining siltation rate and consequently to assess their useful life. The data will also be useful for deriving siltation indices for different regions and river basins for use in the future design of the reservoirs. These surveys will enable selection of appropriate measures for controlling sedimentation along with efficient management and operation of reservoirs. The conventional techniques like boat mounted eco-sounder, HYDAC etc. are time consuming as well as costly. Remote sensing technique can be used to calculate the present live storage capacity of a reservoir due to its synoptic and repetitive coverage. These surveys based on remote sensing data are faster, economical and reliable.

Central Water Commission has been regularly involved in carrying out sedimentation assessment studies of various reservoirs through remote sensing techniques. As a part of 50 reservoirs study which were proposed to be taken up under the plan scheme “Research & Development Programme in Water Sector” during the period 2017-20 (i.e. beyond 12th Five Year Plan) / upto the end of 14th Finance Commission, the work “Sedimentation assessment study of Forty (40) reservoirs in India through Remote Sensing Technique” was awarded to MERI, Nashik. Rest will be carried out in-house. Out of these forty (40) reservoirs, the study of twenty three (23) reservoirs were found feasible and hence, completed. The balance were found non feasible due to non-availability of cloud free imageries or non-attainment of FRL/MDDL.

I would like to compliment Shri. Rishi Srivastava, Director (Remote Sensing Dte), Shri. Ashish Awasthi, Dy. Director (Remote Sensing Dte) and other officers and staff of Remote Sensing Directorate for their dedicated efforts in bringing out this report. I would also like to compliment Shri. Makarand Kulkarni, Executive Engineer (REC, MERI) and his team for timely completion of the report.

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Acknowledgement

The Project Team is thankful for the guidance provided by Chief Engineer (EMO), CWC, and Director, Remote Sensing Directorate, CWC, New Delhi in completing the work of “Sedimentation Assessment Study of Forty (40) Reservoirs in India through Remote Sensing Technique” and in particular the present study of Bhandardara Reservoir.

The project team is thankful to the Secretary (CAD), Water Resources Department, Government of Maharashtra for his keen interest and constant encouragement in completion of this study. Our special thanks are due to Shri. A. P. Kohirkar, Director General, MERI and Shri. S. S. Deshmukh, Superintending Engineer, MERI for their valuable support and motivation for carrying out this work.

Our thanks are also due to Shri. R. N. More, Superintending Engineer and Administrator, Command Area Development Authority, (W.R.D.), Nashik for the keen interest shown in the work. We are also thankful to Shri. G. B. Nannore, Executive Engineer, Ahmednagar Irrigation Division, Ahmednagar; Shri. G. P. Harde, Sub-Divisional Engineer, Shri. A. U. Deshmukh, Assistant Engineer-II, Akole Irrigation Sub-Division, Akole for supplying all relevant data required for the present analysis.

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CONTENTS		
Sr.No.	Description	Page no.
	Foreword	I
	Acknowledgement	II
	Contents	III
	List of Tables and List of Figures	IV
	Abbreviations and Units Used	V
	Executive Summary	VI
1	Introduction	1
2	Sources and Mechanism of Sedimentation	2
3	Control of Sedimentation	6
4	Remote Sensing in Reservoir Sedimentation	6
5	Objectives	7
6	Study Area	7
7	Previous Surveys	8
8	Approach of Present Study	10
9	Data	11
	9.1 Field data	11
	9.2 Satellite data	11
	9.3 Criteria for satellite dates selection	15
10	Software Used	16
11	Methodology	16
	11.1 Procedural flow chart	17
	11.2 Data loading	17
	11.3 Image geo-referencing	17
	11.4 Area extraction	18
	11.5 Water spread area extraction	18
	11.6 Water spread area at regular interval	20
	11.7 Calculation of reservoir capacity	20
	11.8 Comparison with earlier surveys	29
	11.9 Field visit and ground truth	33
12	Results and Discussions	33
13	Limitations	34
14	Conclusions	34
	References	35
	Annexure	
	I Salient Features	36
	II Reservoir Levels Pertaining to Cloud Free Satellite Data	37
	III Ground Truth Scenario	38

Table No.	List of Tables	Page No.
1	Summary of previous surveys	8
2	Status of cloud free levels achieved during 2016 to 2019	10
3	Details of satellite data	11
4	Range of NDWI values for Bhandardara reservoir	19
5	Water spread areas extracted from satellite data	20
6	Areal extent and cumulative live storage capacity of reservoir at regular interval defined from graph	21
7	Comparison of water spread areas of reservoir (Mm ²)	29
8	Comparison of live storage capacity of reservoir (Mm ³)	31
9	Live storage capacity loss due to sedimentation from original survey	33

Figure No.	List of Figures	Page No.
1	Conceptual sketch of density currents in a reservoir	4
2	Longitudinal patterns of sediment deposition in a reservoir	4
3	Conceptual sketch of different levels in a reservoir	5
4	Index map of Bhandardara reservoir, Maharashtra	9
5	FCC's of Bhandardara reservoir, Maharashtra	12
6	Flow chart showing methodology for reservoir capacity estimation	17
7	Water spread areas on different dates of satellite pass	23
8	SRS Elevation-Area curve for Bhandardara reservoir, Maharashtra	24
9	SRS Elevation-Capacity curve for Bhandardara reservoir, Maharashtra	25
10	Elevation-Area curve for different years for Bhandardara reservoir, Maharashtra	26
11	Elevation-Capacity curve for different years for Bhandardara reservoir, Maharashtra	27
12	Modified SRS Elevation-Area-Capacity curve for Bhandardara reservoir, Maharashtra	28

Abbreviations

AOI	Area of Interest
µm	Micrometer
CWC	Central Water Commission
DGPS	Differential Global Positioning System
ERS	European Remote Sensing Satellite
FCC	False Color Composite
FRL	Full Reservoir Level
IR	Infra Red
IRS	Indian Remote Sensing Satellite
LISS	Linear Imaging Self Scanning Sensor
MDDL	Minimum Draw Down Level
MERI	Maharashtra Engineering Research Institute
MOU	Memorandum of Understanding
MWL	Maximum Water Level
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near Infra Red
NRSC	National Remote Sensing Centre
R	Red band
SAT	Shift Along Track
SQRT	Square Root
SRS	Satellite Remote Sensing
WSA	Water Spread Area

Units Used

ha	Hectare
km	Kilometer
m	Meter
Mm²	Million square meter
Mm³	Million cubic meter
sq km	Square kilometer
sq mi	Square mile

EXECUTIVE SUMMARY

Water resources sector has got high priority in all our developmental plans and accordingly large number of dams have been constructed to supply water for domestic, irrigation and industrial purposes. Natural processes like erosion in the catchment area and its deposition in various parts of the reservoir gradually, reduce the capacity of the reservoir. Dead as well as live storage get affected by it. The information about the reduction in capacity is necessary for all planning and operational purposes, which can be obtained through capacity surveys done at regular interval. The Remote Sensing technique can be used to calculate present capacity of the reservoir. It is very useful due to its simple analysis procedure and repetitive coverage by imagery. The surveys based on remote sensing data are faster, economical and more reliable. Department of Water Resources, River development and Ganga Rejuvenation, Ministry of Jalshakti, Government of India has initiated the programme to evaluate capacity of various reservoirs in the country. Accordingly the Central Water Commission has entrusted MERI, Nashik the work of “Sedimentation Assessment Study of Forty (40) Reservoirs in India through Remote Sensing Technique”. The present study is in regard to Bhandardara Reservoir, Maharashtra, India.

Present study aims in updating the elevation-area-capacity curve of Bhandardara Reservoir, Maharashtra, and finding the capacity loss due to sedimentation in live storage. For carrying out the analysis, IRS P6, Resourcesat 2 and Resourcesat 2A LISS III data with 23.5 m resolution have been used. Satellite data for thirteen passes falling between MDDL (698.070 m) and FRL (744.725 m) are used for the analysis.

The Bhandardara dam is located on the Pravara River. The dam site is located near Shendi village in Akole taluka, Ahmednagar district. The project has a designed gross capacity of 312.600 Mm³, with live capacity of 304.100 Mm³.

This study reveals that the present live capacity of reservoir is 307.598 Mm³. It shows no loss in live capacity in a period of 93 (1926-2019) years.

SEDIMENTATION ASSESSMENT OF BHANDARDARA RESERVOIR, MAHARASHTRA, THROUGH SATELLITE REMOTE SENSING

1. Introduction

India – the second largest country in the world in terms of population – has about 17.3% of world's population, about 4% of world's water resources, and 2.44% of total geographical land area of the world. Therefore, in spite of having an average annual average precipitation to the tune of more than 1105 mm/year, the population density (lack of land resources) and per capita water resources availability make India a water-stressed country, as a whole. However, at a regional or basin level, many areas in the country are water-scarce or severely water-scarce owing to the spatial and temporal variability of water resources.

It is estimated that average annual precipitation over India is about 3880 BCM. Out of this precipitation, the average annual water resources availability of the country is about 1999.2 BCM, as estimated by Central Water Commission (CWC) in 2019. The water resources availability situation gets more murkier due to topographical and other constraints. Due to this, the total utilisable water resources in the country are about 1122 BCM (690 BCM of surface water and 432 BCM of groundwater). On one hand, the per-capita water resource availability is reducing due to increasing population and on the other, per-capita water usage is increasing due to industrialisation, urbanisation and change in lifestyles or dietary habits, making the available water resources still dearer.

India has typical monsoon-based climate where more than 75% rainfall occurs in three months i.e. July, August, and September. The total number of rainy days typically are in the tune of only 20-25 days per year (100-150 hours of rain per year) for most parts of the country. As a result, the bulk of annual water (75-80%) in rivers is available only in these three months. Therefore, in order to sustain life and other activities throughout the year from resources that are available only through 20-25 rainy days, it is absolutely essential to store the water in appropriately-sized storage structures (depending upon the topography and hydrology of the area).

So far, India has developed just 257.812 BCM as live storage capacity and 46.765 BCM is under construction. Realising the importance of storage structures, a large number of reservoirs have been built, since independence, during each plan in almost all river basins, except Ganga and Brahmaputra, to tap the available surface water and to utilize it as and when needed. The capacity of reservoirs is gradually reducing due to silting and hence sedimentation of reservoir is of great concern for all the water resources development projects.

Correct assessment of the sedimentation rate is essential for assessing useful life of the reservoir as well as optimum reservoir operation schedule. Since 1958, when it was established that the live storage of reservoir is getting reduced due to siltation, a systematic effort has been made by various departments / organizations to evaluate the capacity of reservoirs. Various techniques like boat echo sounder, etc. being replaced by hydrographic data acquisition system (HYDAC) and HITECH method using Differential Global Positioning System (DGPS). The conventional techniques are found either time consuming or costly and require considerable manpower. Remote sensing technique to calculate the present live capacity of reservoir is found to be very useful in this context due to its synoptic and repetitive coverage. The surveys based on remote sensing data are faster, economical and more reliable.

These surveys will enable selection of appropriate measures for controlling sedimentation along with efficient management and operation of reservoirs thereby deriving maximum benefits for the society.

This report covers the study of Bhandardara reservoir, Maharashtra by Central Water Commission, New Delhi.

2. Sources and Mechanism of Sedimentation

In order to obtain The principal sources of sediments are as follows:

1. Deforestation
2. Excessive erosion in the catchment
3. Disposal of industrial and public wastes
4. Farming
5. Channelisation works
6. Human activities
7. Land development, highways, and mining

The sedimentation is a product of erosion in the catchment areas of the reservoir and hence lesser the rate of erosion, smaller is the sediment load entering the reservoir. Various factors govern the erosion, transport and deposition of sediment in the reservoir. Type of soil, drainage density, vegetation, rainfall intensity and duration, shape of catchment and land use / land cover affect the erosion. Sediment transportation depends upon slope of the catchment, channel geometry and nature of riverbank and bed. Deposition is a function of bed slope of the reservoir, length of reservoir, flow patterns, inflow - outflow rates, grain size distribution, mode of reservoir operation, etc.

In order to obtain the knowledge of sedimentation in the reservoir, it is necessary to study the mechanism of sedimentation, which will help to mitigate reservoir sedimentation, prolong the life span of reservoirs and to take full benefits of reservoirs. The sediment deposition in a reservoir depends on the following:

- Longitudinal and lateral valley shape
- Length and shape of reservoir
- Flow patterns in reservoir
- Capacity to inflow volume ratio (trap efficiency)
- Grain size distribution of sediment
- Water and sediment discharges
- Mode of reservoir operation
- Nature of incoming floods

Reservoirs created by dams on rivers lose their storage capacity due to sedimentation. As water enters a reservoir, its velocity diminishes because of the increased cross-sectional area of the channel. If the water stored in the reservoir is clear and the inflow is muddy, the two fluids have different densities and the heavy turbid water flows along the channel bottom towards the dam under the influence of gravity (Figure 1). This condition is known as "stratified flow" and the underflow is called a "density current". A large proportion of the transported silt eventually gets deposited at different levels of a reservoir and causes reduction not only in dead storage but also in live storage capacities.

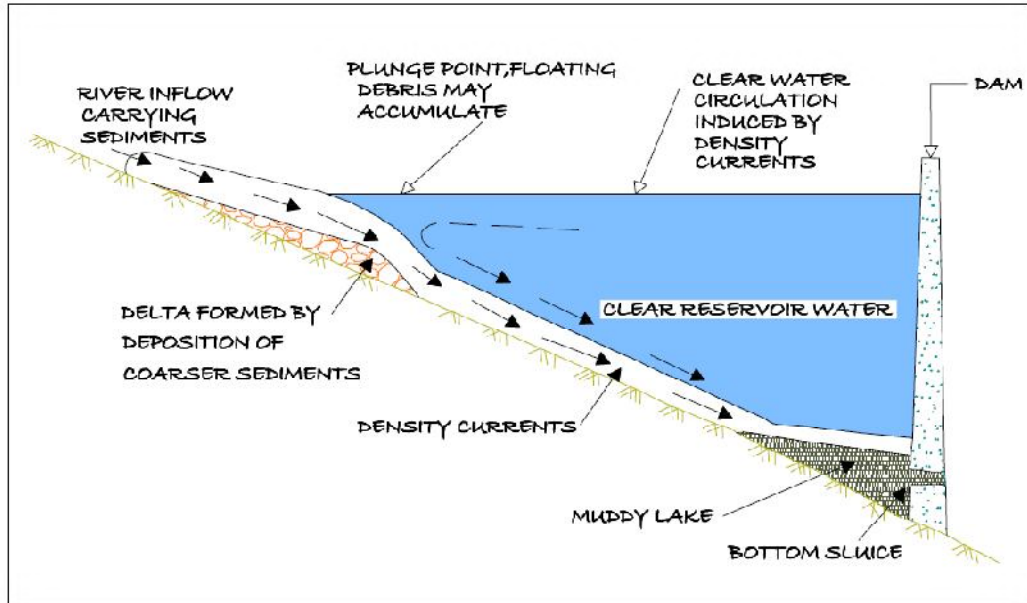


Figure 1 : Conceptual sketch of density currents in a reservoir

Earlier it was believed that sediment always gets deposited in the bottom elevations of reservoir affecting the dead storage rather than depositing throughout the full range of reservoir depth. It is now fully realized that deposition takes place throughout the reservoir reducing the incremental capacity at all elevations.

Longitudinal deposition patterns in the reservoir will vary from one reservoir to another as influenced by pool geometry, discharge and grain size characteristic of the inflowing load and reservoir operation. There can be four types of depositing patterns in the reservoir as shown in the Figure 2.

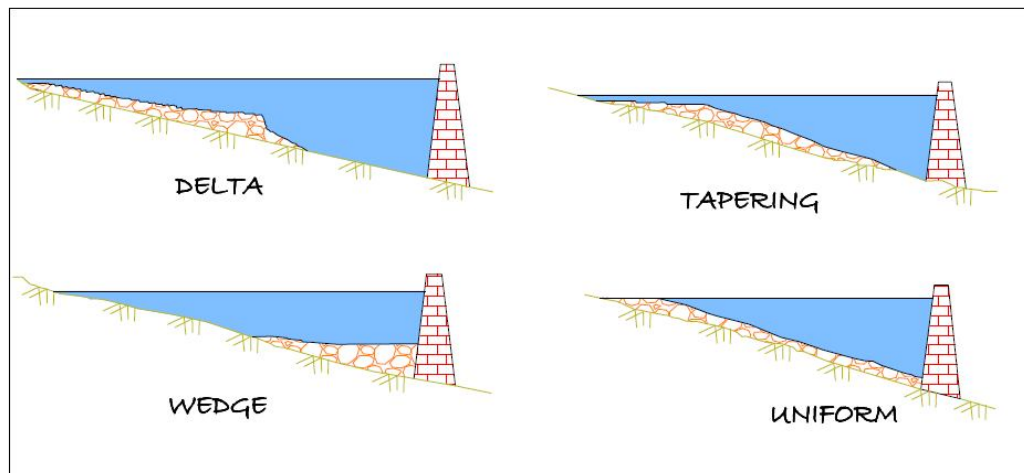


Figure 2 : Longitudinal patterns of sediment deposition in a reservoir

Delta deposits contain the coarsest fraction of the sediment load, which is rapidly deposited at the zone of inflow. It may consist entirely of coarse sediment or may also contain a large fraction of finer sediment such as silt. Wedge-shaped deposits are thickest at the dam and become thinner moving upstream. This pattern is typically caused by the transport of fine sediment to the dam by turbidity currents. Wedge-shaped deposits are also found in small reservoirs with a large inflow of fine sediment, and in large reservoirs operated at low water level during flood events, which causes most sediment to be carried into the vicinity of the dam. Tapering deposits occur when deposits become progressively thinner moving toward the dam. This is a common pattern in long reservoirs normally held at high pool level, and reflects the progressive deposition of fines from the water moving toward the dam. Uniform deposits are unusual but do occur. Narrow reservoirs with frequent water level fluctuation and small load of fine sediment can produce nearly uniform deposition depths. Several factors like amount of sediment load, size distribution, fluctuations in stream discharge, shape of reservoir, stream valley slope, vegetation at the head of the reservoir, location and size of reservoir, outlets, etc., control the location of sediment deposits in the reservoir.

Figure 3 shows different levels in the reservoir where-in the capacity is affected. Reservoirs operate between Minimum Draw Down Level (MDDL), which is at sluice level to Full Reservoir Level (FRL), which is at dam level. The storage between these two levels is the live storage as shown in Figure 3. The storage below MDDL is the dead storage. Water stored along the valley bed is known as valley storage.

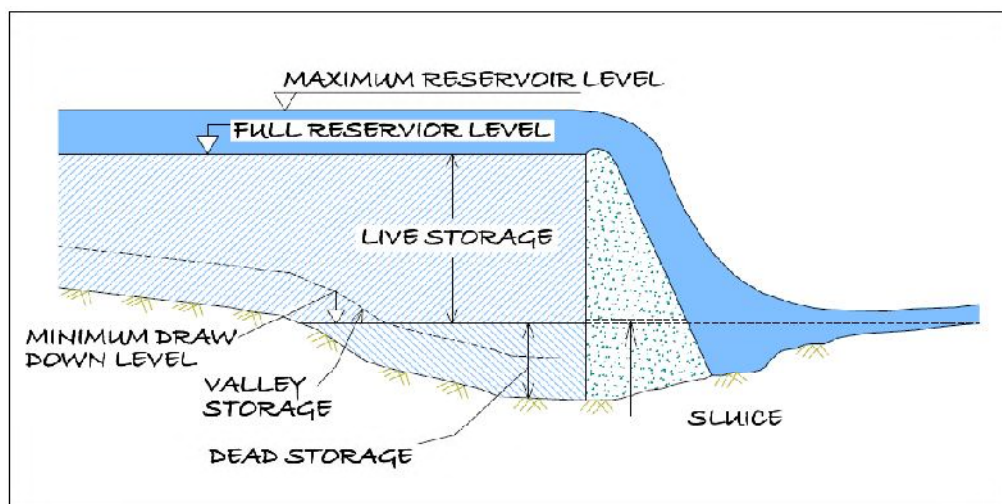


Figure 3 : Conceptual sketch of different levels in a reservoir

3. Control of Sedimentation

Due to the multiple variables involved in reservoir sedimentation, no single control measure can be considered as the most effective. The measures, which can be employed to limit sedimentation and turbidity, are as under:

1. Soil and water conservation measures within the drainage basin, contour ploughing, strip cropping, suitable farming practices, improvement of agricultural land, construction of small dams/ponds/terraces/check dams on gullies
2. Revetment and vegetation cover
3. Evacuation of sediment
4. Reservoir shoreline protection
5. Stream bank and flood plain protection
6. Ridge plantation such as pasture development and reservoir shoreline protection

Silting not only occurs in the dead storage but also encroaches into the live storage zone, which impairs the intended benefits from the reservoirs. Therefore, the problem of sedimentation needs careful consideration. Adequate provision has to be made in the reservoir for accumulation of anticipated quantities of silt. Steps are also required to be taken to ensure that the storage capacities available are not lost or get reduced by accelerated sedimentation.

4. Remote Sensing in Reservoir Sedimentation

Remote sensing is the art and science of collecting information about earth's feature without being in physical contact with it. Various features on earth surface reflect or emit electromagnetic energy depending upon their characteristics. The reflected radiation depends upon physical properties of the terrain and emitted radiation depends upon temperature and emissivity. The radiations are recorded by the sensors onboard satellite and then are transmitted back to earth. Discrimination between features depends on the fact that the response from different features like vegetation, soil, water is different and discernable. Data received at ground stations, is digitally or visually interpreted to generate thematic maps.

Data acquisition is done from various polar orbiting satellites (orbiting around 800 to 900 km altitude), namely Indian Remote Sensing (IRS) satellite, European Remote Sensing (ERS) satellite, Landsat and SPOT satellites. Data from these satellites are being received and archived by National Remote Sensing Centre (NRSC) at Hyderabad.

Present study utilizes data from IRS P6, Resourcesat 2 and Resourcesat 2A satellite. They have LISS III sensor, which operates in four spectral bands. Three bands are in the visible and near infra red region with spectral band widths as 0.52-0.59 μm , 0.62-0.68 μm and 0.77-0.86 μm and spatial resolution as 23.5 m. Fourth band with spectral bandwidth of 1.55-1.75 μm falls in short wave infra red region.

Reservoir sedimentation surveys are essentially based on mapping of water-spread areas at the time of satellite over pass. It uses the fact that water-spread area of the reservoir reduces with the sedimentation at different levels. The water-spread area and the elevation information are used to calculate the volume of water stored between different levels. These capacity values are then compared with the previously calculated capacity values to find out change in capacity between different levels.

5. Objectives

The objective of the study is to estimate capacity loss of Bhandardara reservoir due to sedimentation through satellite remote sensing. Following objectives will be achieved in the study.

- (i) Updating of Elevation-Area-Capacity curve using satellite data in live storage zone of Bhandardara reservoir.
- (ii) Estimation of live storage loss due to sedimentation in Bhandardara reservoir.

6. Study Area

The Bhandardara dam is located near Shendi village in Akole taluka, Ahmednagar district, on the Pravara river. The dam site is located at 19° 32' 30" N latitude and 73° 45' 47" E longitude. The location of the dam is shown in Figure 4 as Index Map. The Bhandardara dam serves dual purpose of irrigation and electricity generation. The dam was completed in the year 1926. The MWL, HFL and FRL of the reservoir are at level of 746.035 m, 745.020 m and 744.725 m respectively. The dead storage and live

storage capacity of Bhandardara dam are 8.500 Mm³ and 304.100 Mm³ respectively. The sill level of the head regulators taking off water from the dam at 50, 100, 150 and 200 feet from bottom of dam are 678.980 m, 694.220 m, 709.460 m and 724.700 m respectively.

The river Pravara has its source in the eastern slopes of the Sahyadri Ghat, in a western zone of Maharashtra State. It is a tributary of Godavari river. The catchment area of the reservoir is 122.00 sqkm. Annual rainfall on top of Sahyadri is 5460 mm and at dam site is 3225 mm.

There are two main canals taking off from the reservoir. The length of right bank canal (RBC) is 52.80 km and its Gross Command Area is 29866 ha. The length of left bank canal (LBC) is 76.80 km with Gross Command Area 59625 ha. Salient features of Bhandardara project are given in Annexure I.

7. Previous Surveys

Details of previous surveys are mentioned below as per Table 1.

Table 1 : Summary of previous survey

		Design survey 1926	SRS survey 2004	SRS survey 2015
Live capacity (Mm ³)		304.10	304.10	304.10
SRS survey studied live storage zone				
Study Portion	Highest RL (m)	-	744.870	744.700
	Lowest RL (m)	-	708.790	713.480
	Studied capacity (Mm ³)	-	290.867	273.460
Observed SRS capacity (Mm ³)		-	296.161	276.663
Increase / loss in capacity		-	Increased	Increased

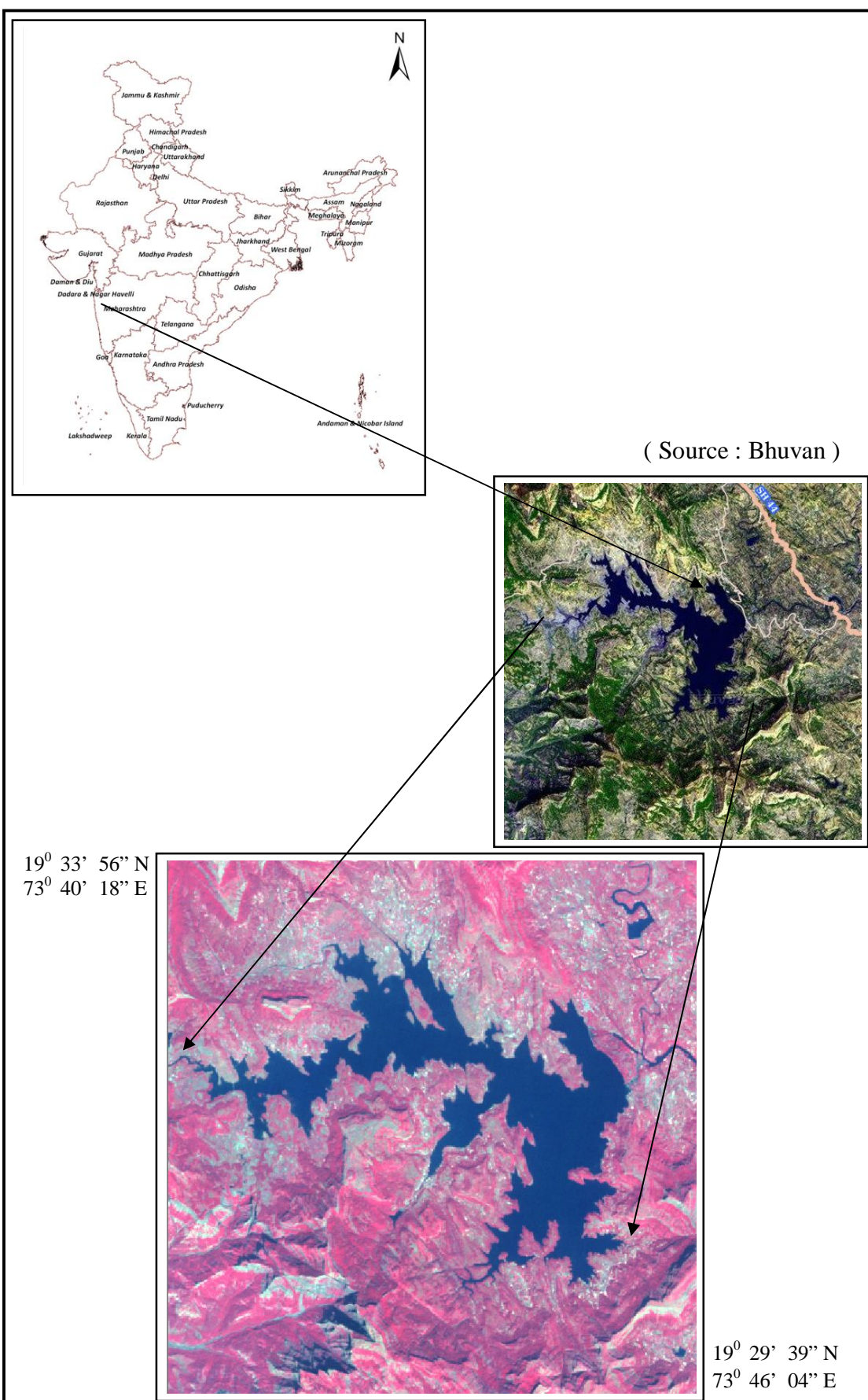


Figure 4 : Index map of Bhandardara reservoir, Maharashtra

8. Approach of Present Study

Remote sensing technique is utilized to assess the sedimentation between operating levels of reservoir. This operating range between MDDL (698.070 m) and FRL (744.725 m) varies each year and depends upon yield in the reservoir and utilization of water. During 2016 to 2019 the minimum and maximum levels in this reservoir fluctuated in various ranges. They are shown in Table 2. The cloud free levels in this range are selected for analysis.

Table 2 : Status of cloud free levels achieved during 2016 to 2019

Sr. No.	Water year	Minimum level (m)	Maximum level (m)	Difference of minimum and maximum levels (m)
1	2015-2016	710.990	715.120	4.130
2	2016-2017	724.520	735.510	10.990
3	2017-2018	731.800	744.725	12.925
4	2018-2019	700.680	729.270	28.590

The information reveals that in the water year 2017-2018, reservoir was filled up to FRL at 744.725 m while it got depleted close to MDDL in 2018-2019. For present study, two images from water year 2015-2016, two images from water year 2016-2017, four images from water year 2017-2018 and five images from water year 2018-2019 have been used. The year of survey of present study is treated as year 2018-2019.

9. Data

9.1 Field data

Following data set was obtained from Executive Engineer, Ahmednagar Irrigation Division, Ahmednagar for Bhandardara reservoir and used in the analysis.

- i) Index map of reservoir
- ii) Latitude and longitude of the reservoir
- iii) Original area capacity table at 1m interval.
- iv) Salient features of the project
- v) Reservoir levels for given dates of satellite pass.

9.2 Satellite data

IRS P6, Resourcesat 2 and 2A LISS III images of 23.5 m resolution having Path 95, Row 59 have been used in present analysis. The FCC of the images are as given in Figure 5. The dates of satellite pass of selected images and corresponding reservoir levels are given in Table 3.

Table 3 : Details of satellite data

Sr. No.	Date of pass	Elevation (m)
1	11-Jun-2019	700.680
2	18-May-2019	709.120
3	09-May-2016	710.990
4	27-Apr-2016	715.120
5	24-Mar-2019	720.710
6	16-May-2017	724.520
7	07-Mar-2019	726.070
8	23-Feb-2019	729.270
9	29-Apr-2018	731.800
10	29-Mar-2017	735.510
11	24-Mar-2018	738.940
12	28-Feb-2018	741.800
13	31-Oct-2017	744.725

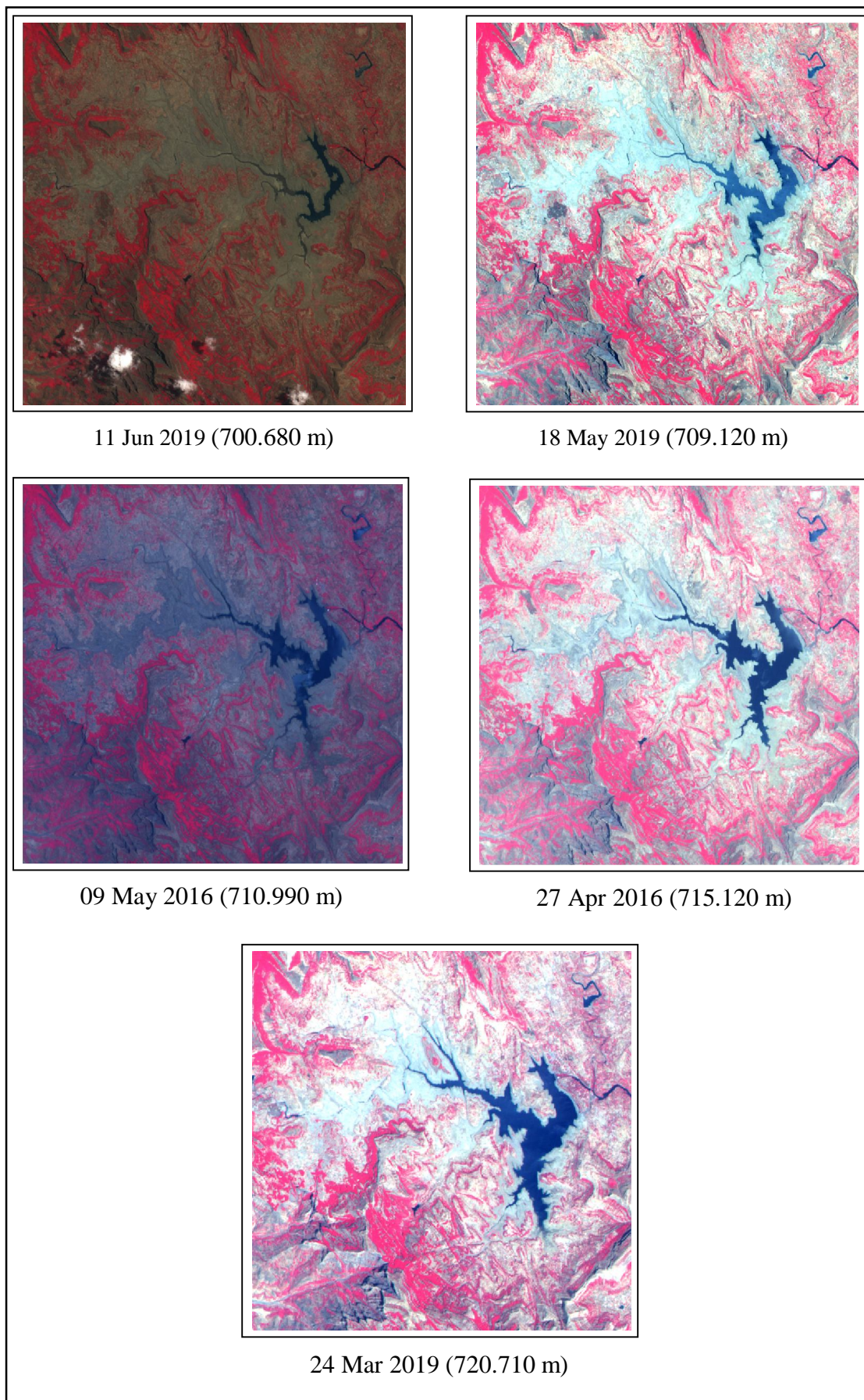


Figure 5 : FCC's of Bhandardara reservoir, Maharashtra (Conti.)

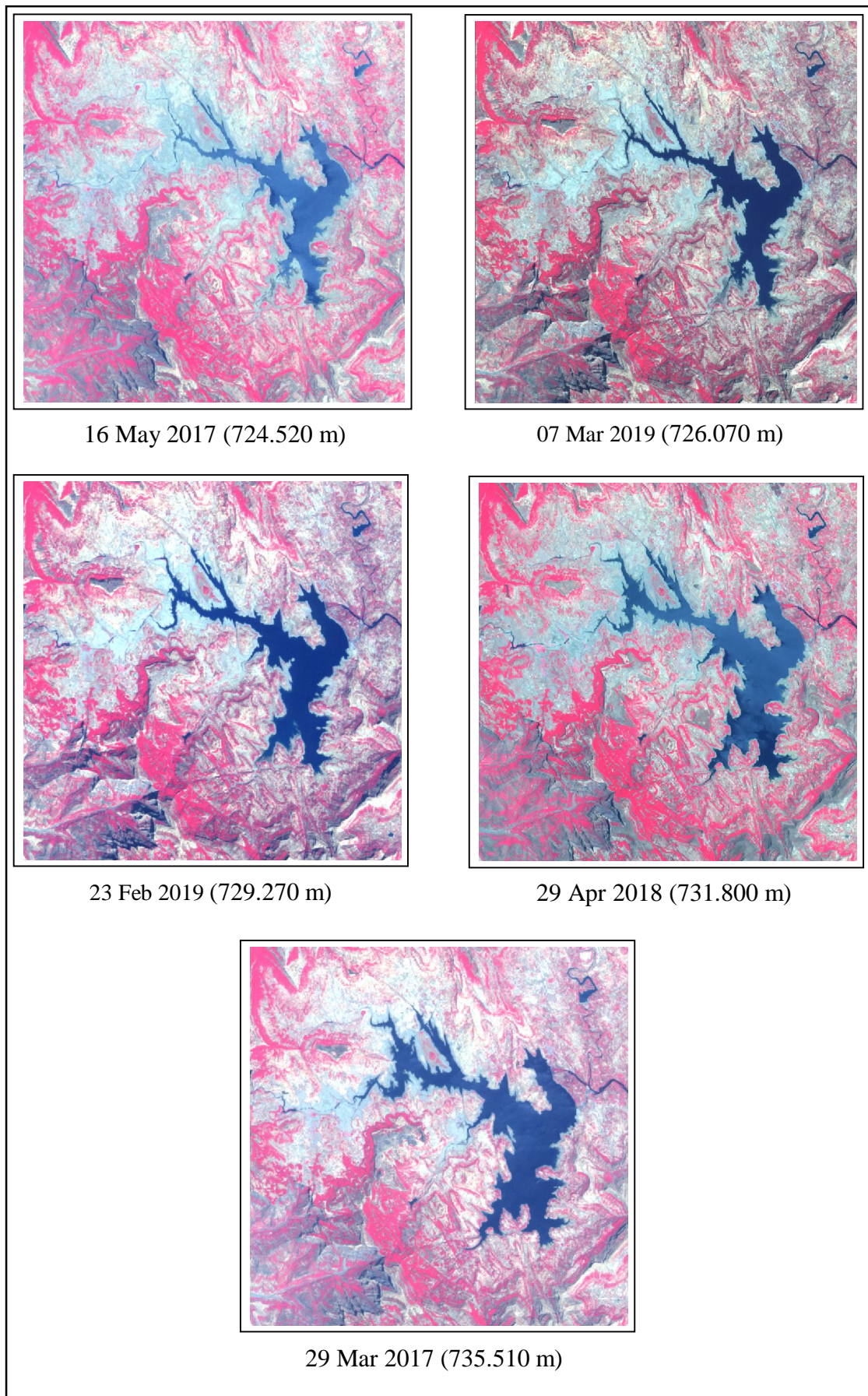


Figure 5 : FCC's of Bhandardara reservoir, Maharashtra (Conti.)

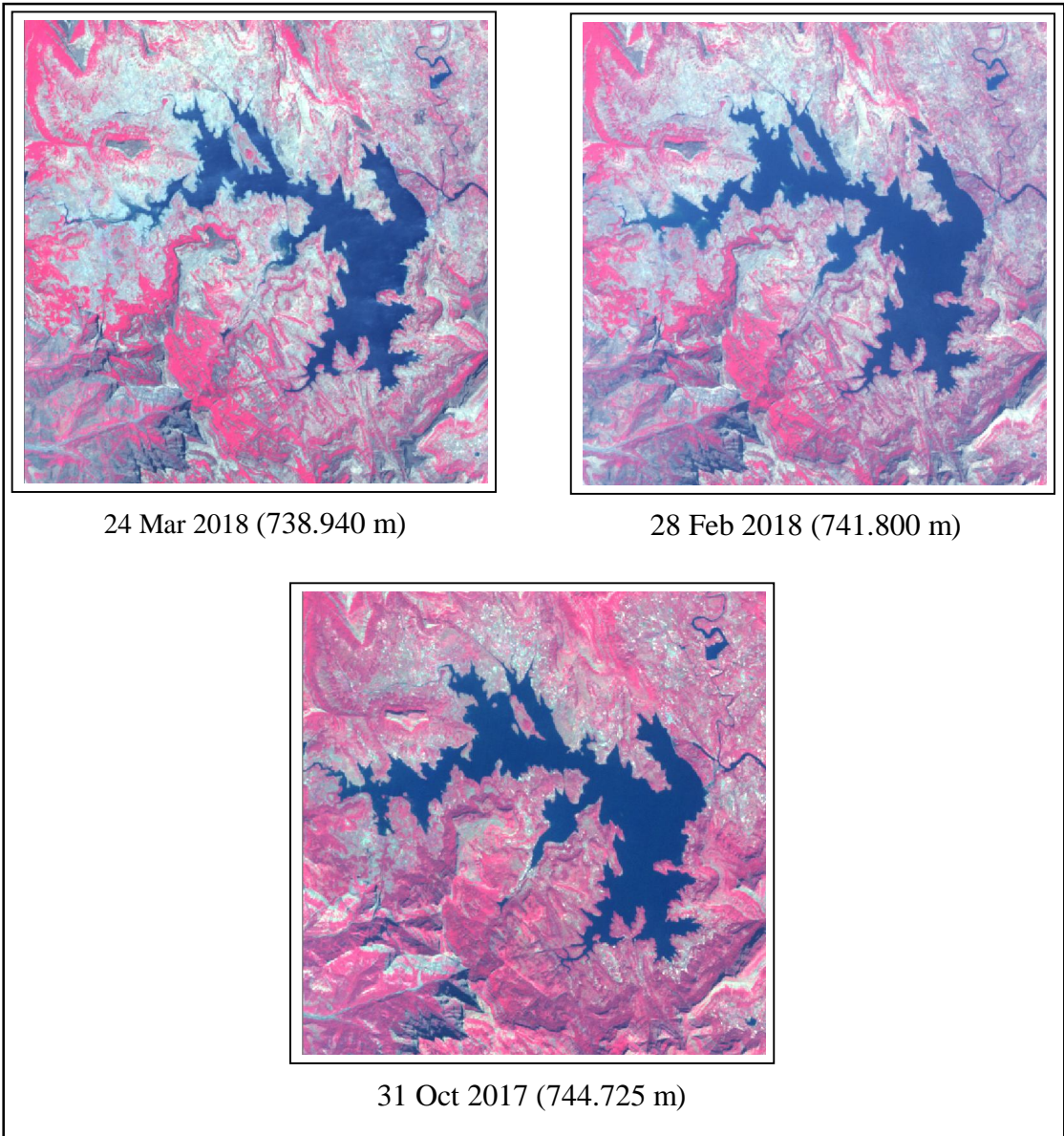


Figure 5 : FCC's of Bhandardara reservoir, Maharashtra

9.3 Criteria for satellite dates selection

The selection of the satellite data for the present study is based on the following guidelines given in the MOU signed between CWC, New Delhi and MERI, Nashik.

- (i) To carry out the feasibility assessment of the given reservoir regarding availability of cloud free satellite data of dates of satellite pass corresponding to reservoir levels near MDDL as well as near FRL and at uniform interval to the extent possible in between MDDL and FRL for the latest water year or maximum up to two previous water years.
- (ii) To carry out sedimentation analysis through SRS technique to cover the entire live storage zone of the reservoir.
- (iii) In case of inability to cover the entire live storage zone of the reservoir due to non-availability of cloud free satellite data at FRL and MDDL, the study may be taken up if minimum of 80 % of live storage capacity is covered by the available cloud free dates of satellite pass on maximum and minimum reservoir levels.

NRSC website has been browsed to prepare a list of dates of satellite pass over the Bhandardara reservoir for the year 2016 to 2019. The reservoir levels on these dates along with corresponding water spread areas and capacities have been obtained from field officers.

The reservoir has been depleted up to 700.680 m as against MDDL (698.070 m). The maximum level covered in the present study is 744.725 m, which is FRL (744.725 m). Variation in the study level is $(744.725 - 700.680) = 44.045$ m. The difference between FRL and MDDL is $(744.725 - 698.070) = 46.655$ m.

In the present study, storage of 301.160 Mm^3 has been covered as against total live capacity of 304.100 Mm^3 . Thus the percentage live storage covered by this study is 99.03 %. (Annexure II)

Statement giving cloud free dates of satellite pass, reservoir levels, areas and capacities for the Bhandardara reservoir has been prepared and submitted to CWC. The CWC has finalized the dates and placed order of images with NRSC, Hyderabad. The data has been received directly to MERI from NRSC, Hyderabad.

10. Software Used

The analysis is done using the software ERDAS IMAGINE Ver. 2010. This software provides facility for satellite image analysis, by different methods.

11. Methodology

The basic approach is to find out the water-spread areas from satellite data for different water levels between MDDL to FRL. The difference between areal spread of water between current year and earlier years is the areal extent of silting at these levels. The methodology for estimation of live capacity of reservoir using remote sensing consists of following major tasks

- (i) Digital data base creation
- (ii) Estimation of water-spread area
- (iii) Calculation of reservoir capacity
- (iv) Comparison of result with previous surveys
- (v) Estimation of live capacity loss due to sedimentation

11.1 Procedural flow chart

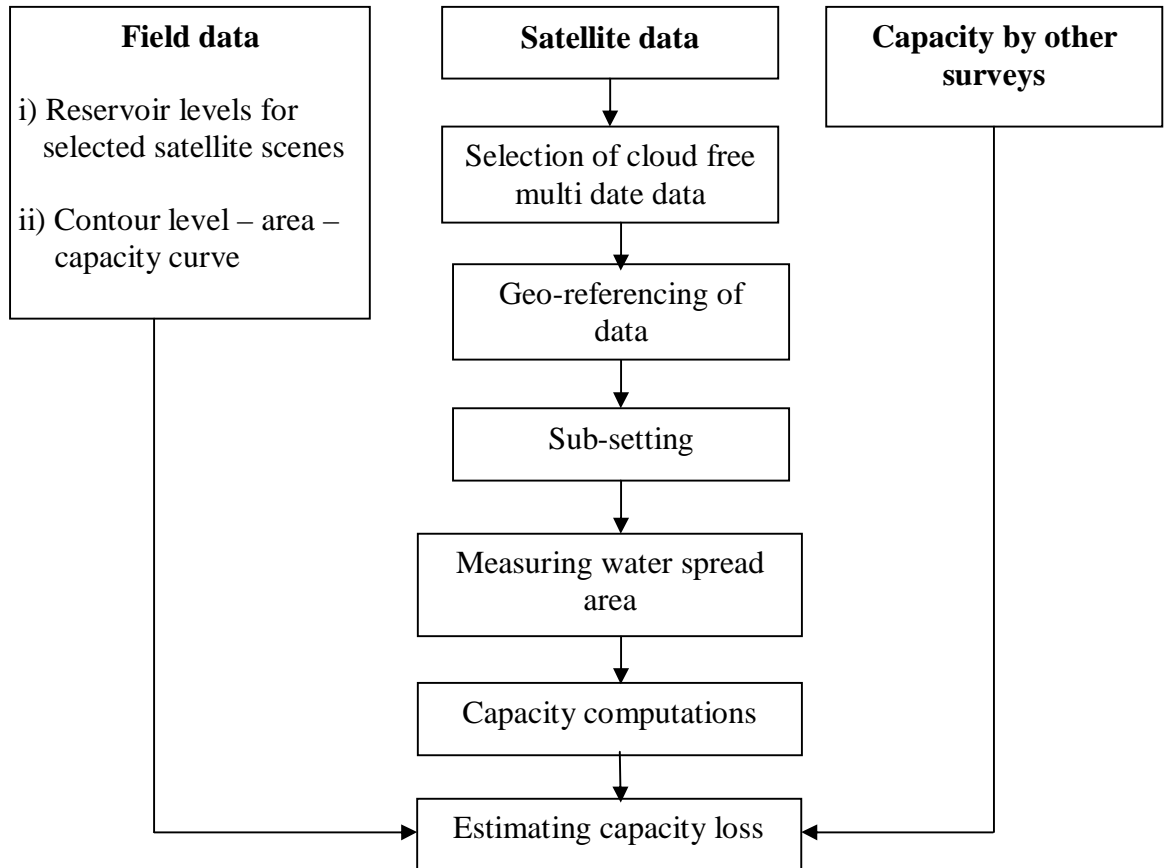


Figure 6 : Flow chart showing methodology for reservoir capacity estimation

11.2 Data loading

All the scenes are loaded in the system. These are listed as different files. They are renamed corresponding to falling levels. It helps in identifying the images during analysis. These files are in .img formats.

11.3 Image geo-referencing

Geo-referenced ready satellite images have been used in the analysis. However, when all the images are superimposed and swiped, slight displacements of images are noticed. Treating the image of the highest water level as the base image all the remaining images are again geo-referenced using image to image option of the ERDAS IMAGINE software.

11.4 Area extraction

A subset of the rectified scene is defined so as to facilitate and use in subsequent analysis. Rectified scene is loaded on the system. A small area around reservoir is extracted from one scene in interactive way. Once the area of interest (AOI) is finalized other scenes are extracted using the same AOI.

11.5 Water spread area extraction

There are various methods for the extraction of water area information from remote sensing imagery, which, according to the number of bands used, are generally divided into two categories, i.e. single-band and multi-band methods.

The multi-band method takes advantage of reflective differences of each involved band. There are two ways to extract water information using the multi-band method. One is through analyzing signature features of each ground target among different spectral bands, finding out the signature differences between water and other targets based on the analysis, and then using an if-then-else logic tree to delineate land from open water.

The other one is a band-ratio approach using two multispectral bands. One is taken from visible wavelengths and is divided by the other usually from near infrared (NIR) wavelengths. As a result, vegetation and land presences are suppressed while water features are enhanced. However, the method can suppress non-water features but do not remove them, and therefore the Normalized Difference Water Index (NDWI) was proposed by Mc Feeters (1996) to achieve this goal.

The NDWI is expressed as follows (Mc Feeters 1996):

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

Where Green is a green band such as TM band 1, and NIR is a near infrared band such as TM band 3.

This index is designed to

- (1) maximize reflectance of water by using green wavelengths;
- (2) minimize the low reflectance of NIR by water features; and
- (3) take advantage of the high reflectance of NIR by vegetation and soil features.

As a result, vegetation and land presences are suppressed while water features are enhanced.

Table 4 : Range of NDWI values for Bhandardara reservoir

Date of pass	Minimum value	Maximum value
11-Jun-2019	0.0888	0.3254
18-May-2019	0.0490	0.2604
09-May-2016	0.3388	0.5242
27-Apr-2016	0.0024	0.2726
24-Mar-2019	0.0243	0.2293
16-May-2017	-0.0159	0.1406
07-Mar-2019	0.1371	0.4722
23-Feb-2019	0.0697	0.2928
29-Apr-2018	0.1362	0.3366
29-Mar-2017	0.0012	0.2341
24-Mar-2018	-0.0143	0.3329
28-Feb-2018	0.0141	0.2326
31-Oct-2017	-0.0652	0.2340

Using the above range of values, water spread areas are extracted for all the scenes. The Water Spread Areas (WSA) derived for all the scenes and their corresponding water levels are shown in Table 5.

Table 5 : Water spread areas extracted from satellite data

Date of pass	Elevation (m)	Area (Mm ²)
11-Jun-2019	700.680	0.906
18-May-2019	709.120	2.431
09-May-2016	710.990	3.057
27-Apr-2016	715.120	3.568
24-Mar-2019	720.710	4.784
16-May-2017	724.520	5.826
07-Mar-2019	726.070	6.423
23-Feb-2019	729.270	7.839
29-Apr-2018	731.800	9.380
29-Mar-2017	735.510	11.227
24-Mar-2018	738.940	13.820
28-Feb-2018	741.800	16.366
31-Oct-2017	744.725	18.652

The water spread areas on selected dates of satellite pass are shown in Figure 7. The tail of the reservoir is defined by removing the river portion from extracted WSA, carefully.

11.6 Water spread area at regular interval

Water levels on the dates of pass for selected satellite data are not available at regular interval. However to get WSA values at regular interval of elevation, area-elevation curve is plotted for the reservoir and a third order polynomial has been fitted. The areas at an elevation interval of 1.0 m are computed from this best fit equation. These values are given in Table 6.

11.7 Calculation of reservoir capacity

Computation of reservoir capacities at different elevations have been derived using following formula

$$V = H / 3 * (A_1 + A_2 + \text{SQRT} (A_1 * A_2)).$$

Where V is reservoir capacity between two successive elevation of h_1 and h_2

H is the elevation difference, $H = (h_1 - h_2)$

A_1 and A_2 are areas of reservoir water spread at elevation h_1 and h_2 respectively.

The cumulative live capacities derived at different elevation have been shown in Table 6.

Table 6 : Areal extent and cumulative live storage capacity of reservoir at regular interval defined from graph

Water elevation (m)	Water spread area Mm^2 (2018-19)	Cumulative capacity Mm^3 (2018-19)
MDDL 698.070	0.422	0.000
699.000	0.628	0.485
700.000	0.839	1.216
701.000	1.040	2.154
702.000	1.233	3.289
703.000	1.418	4.613
704.000	1.598	6.120
705.000	1.772	7.804
706.000	1.943	9.661
707.000	2.112	11.688
708.000	2.280	13.883
709.000	2.448	16.247
710.000	2.617	18.779
711.000	2.789	21.482
712.000	2.965	24.359
713.000	3.147	27.415
714.000	3.334	30.655
715.000	3.530	34.087
716.000	3.735	37.719
717.000	3.950	41.561
718.000	4.176	45.623
719.000	4.415	49.918

Water elevation (m)	Water spread area Mm² (2018-19)	Cumulative capacity Mm³ (2018-19)
720.000	4.668	54.459
721.000	4.937	59.261
722.000	5.222	64.340
723.000	5.525	69.713
724.000	5.847	75.398
725.000	6.189	81.415
726.000	6.552	87.785
727.000	6.939	94.530
728.000	7.349	101.673
729.000	7.785	109.239
730.000	8.248	117.254
731.000	8.738	125.746
732.000	9.257	134.742
733.000	9.807	144.273
734.000	10.388	154.369
735.000	11.002	165.063
736.000	11.650	176.387
737.000	12.334	188.377
738.000	13.054	201.069
739.000	13.812	214.500
740.000	14.609	228.709
741.000	15.446	243.735
742.000	16.325	259.618
743.000	17.247	276.402
744.000	18.213	294.130
FRL 744.725	18.942	307.598

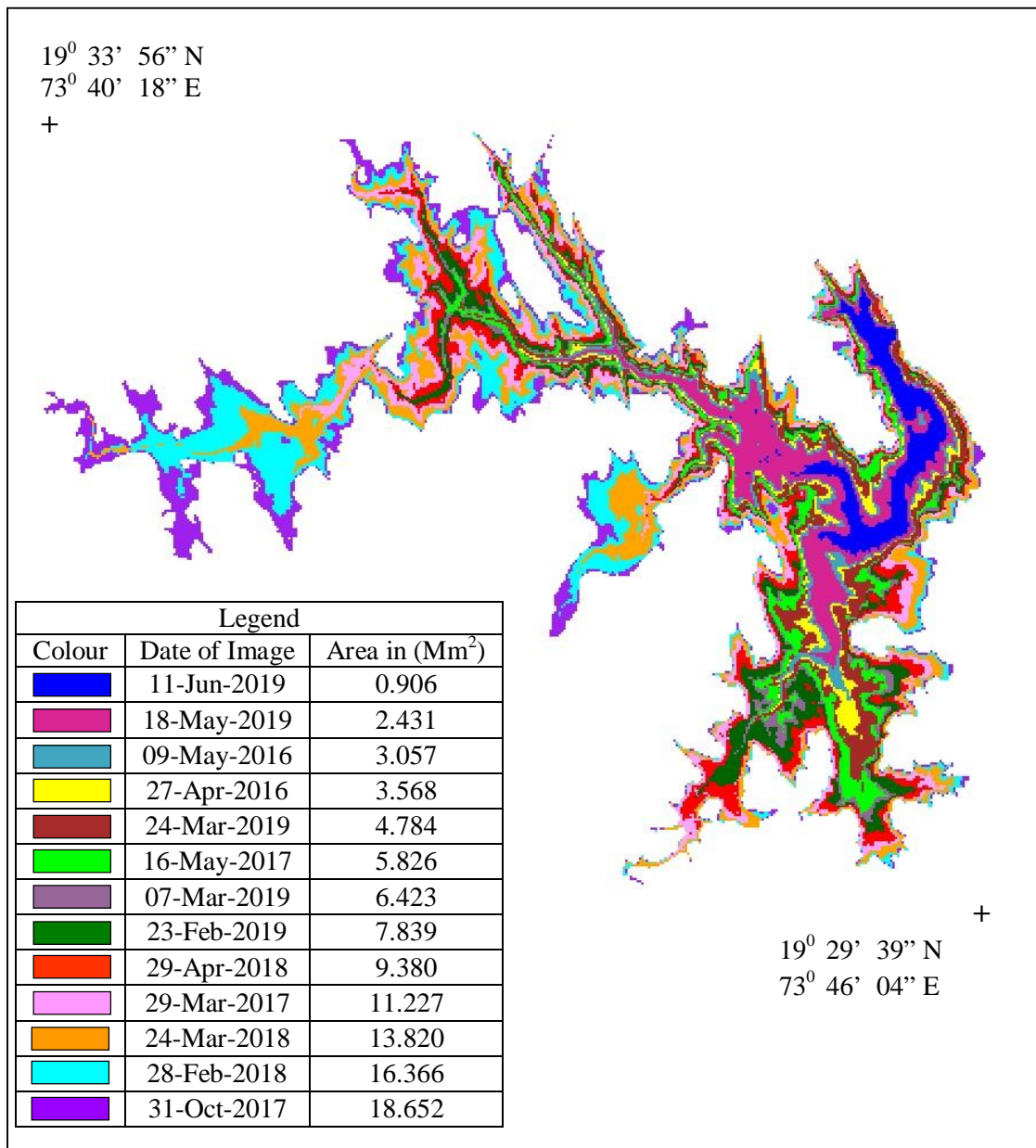


Figure 7 : Water spread areas on different dates of satellite pass

SRS elevation area curve is shown in Figure 8 and tabulated in Table 5. Elevation capacity curves is shown in Figure 9 and tabulated in Table 6. The elevation-area curve drawn through original and present surveys carried out for Bhandardara reservoir are shown in Figure 10 which is based on Table 7. The elevation-capacity curve drawn through original and present surveys carried for the Bhandardara reservoir are shown in Figure 11 and tabulated in Table 8. In Figure 12 updated SRS elevation-area-capacity curve is drawn and tabulated in Table 6.

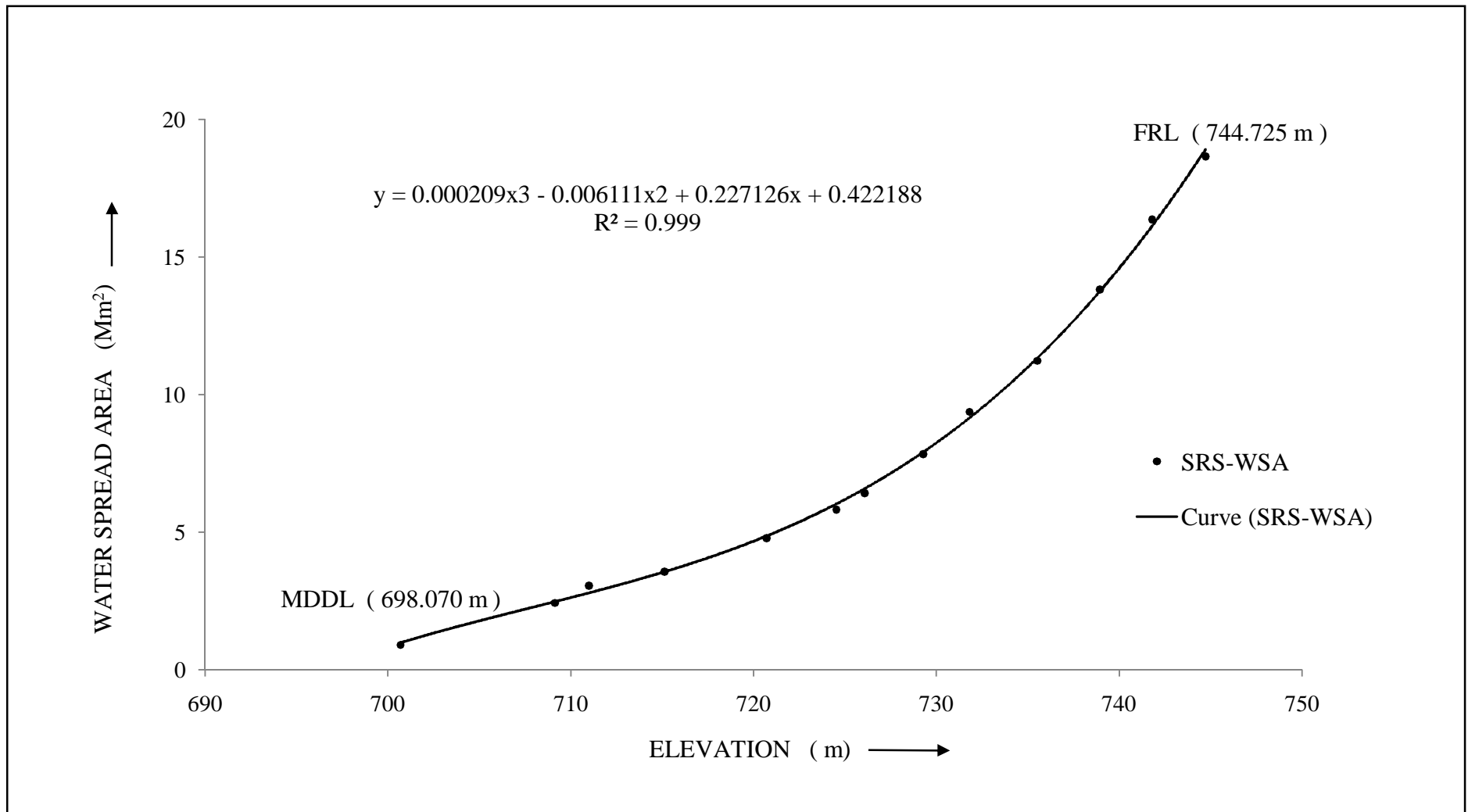


Figure 8 : SRS Elevation-Area curve for Bhandardara reservoir, Maharashtra

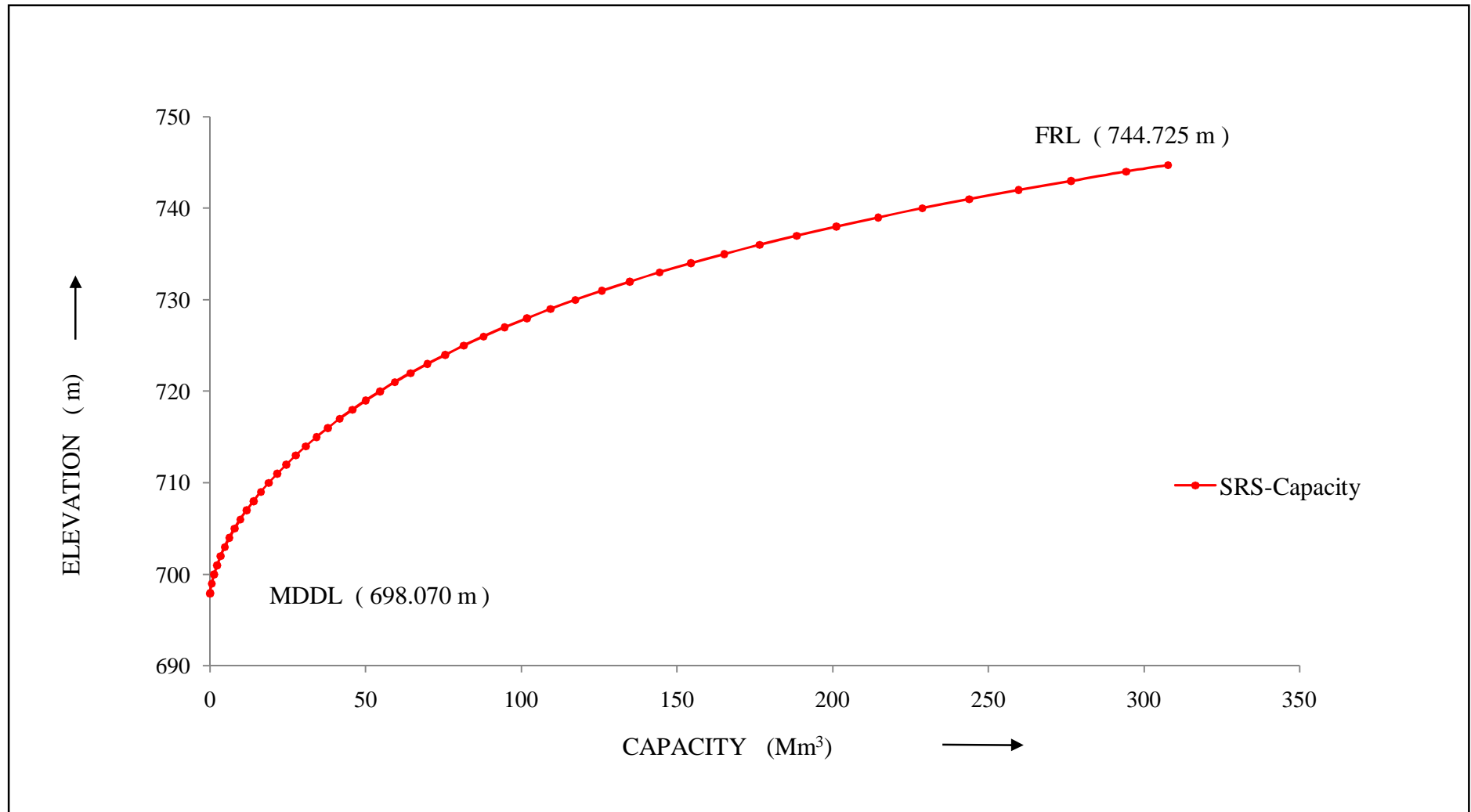


Figure 9 : SRS Elevation-Capacity curve for Bhandardara reservoir, Maharashtra

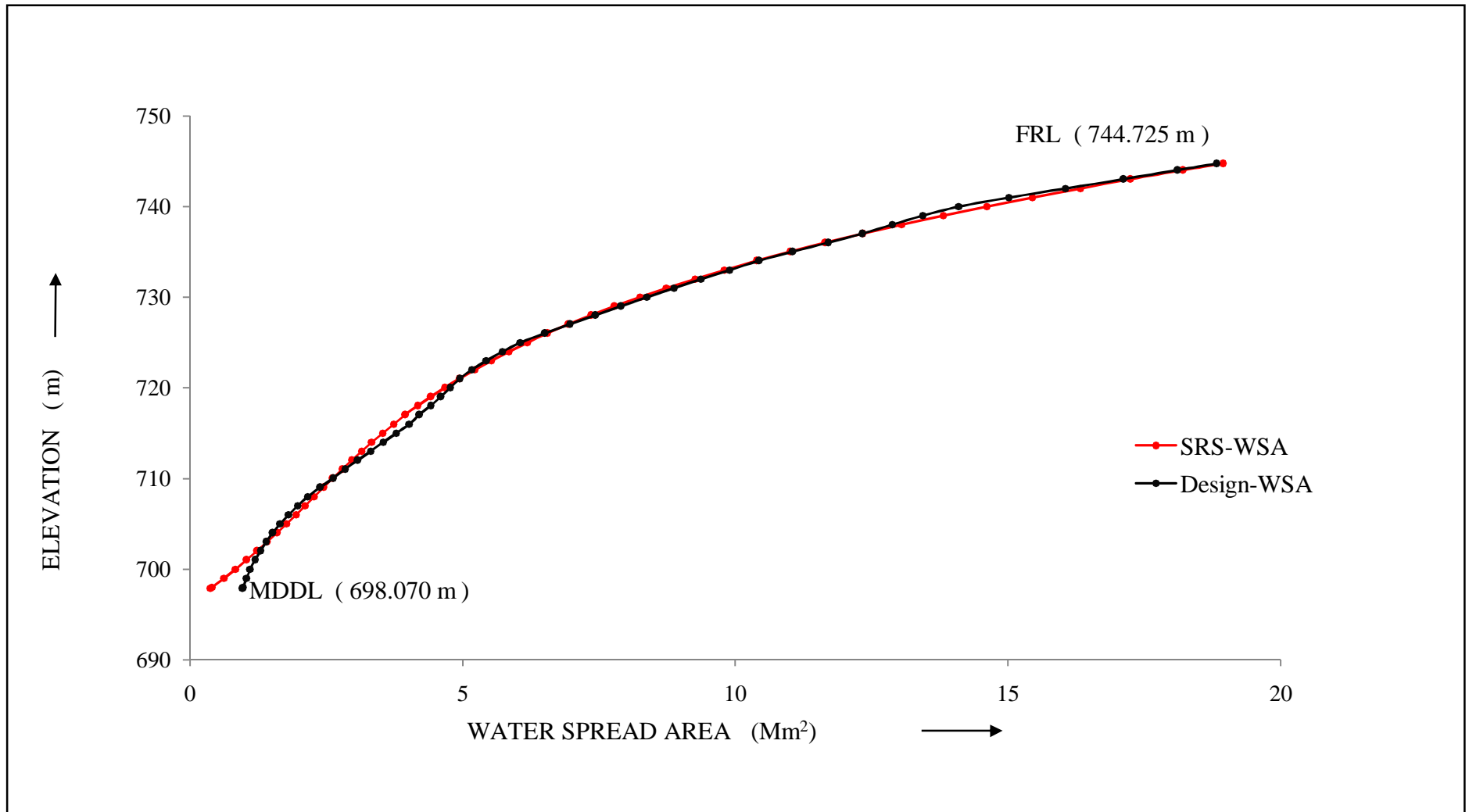


Figure 10 : Elevation-Area curve for different years for Bhandardara reservoir, Maharashtra

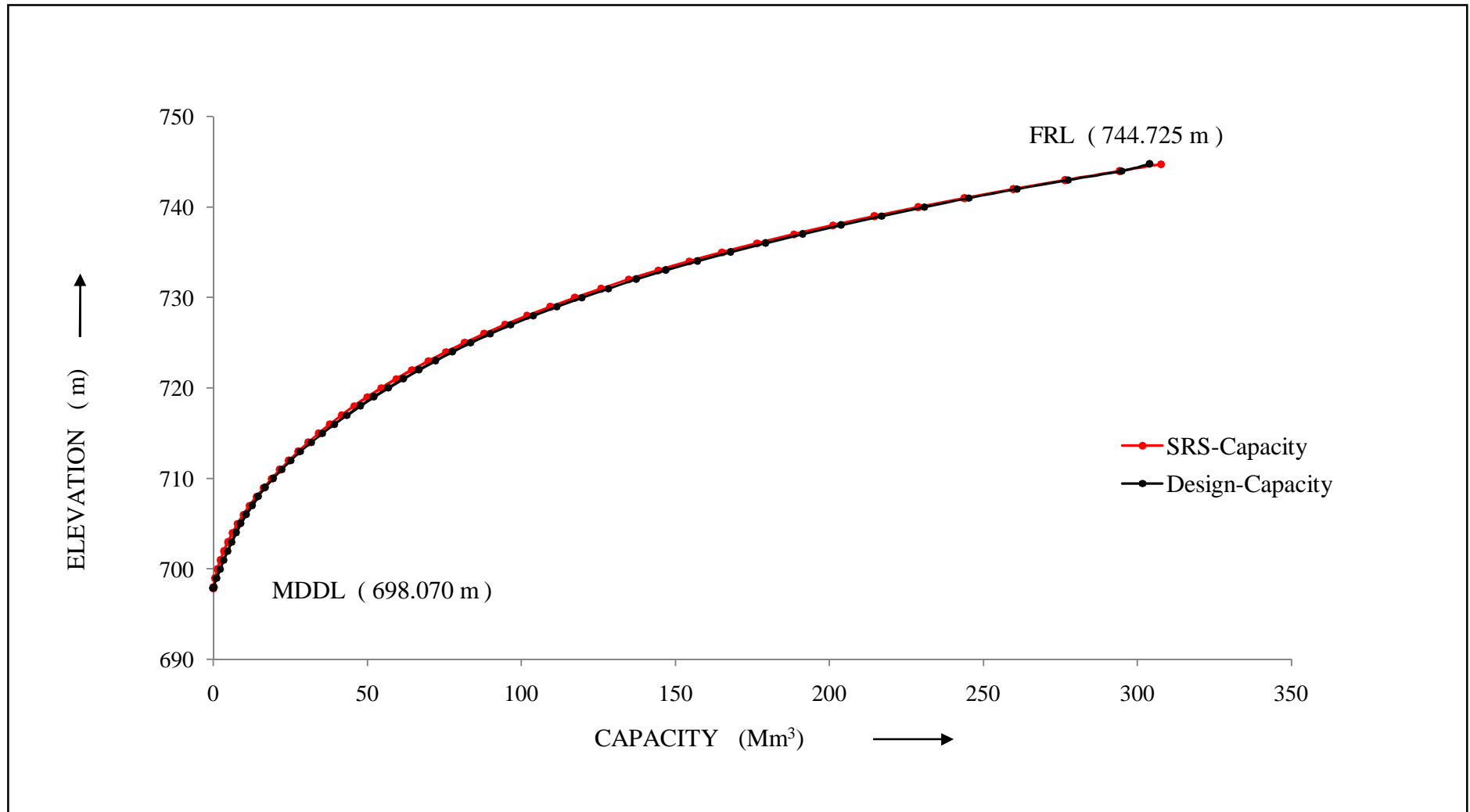


Figure 11 : Elevation-Capacity curve for different years for Bhandardara reservoir, Maharashtra

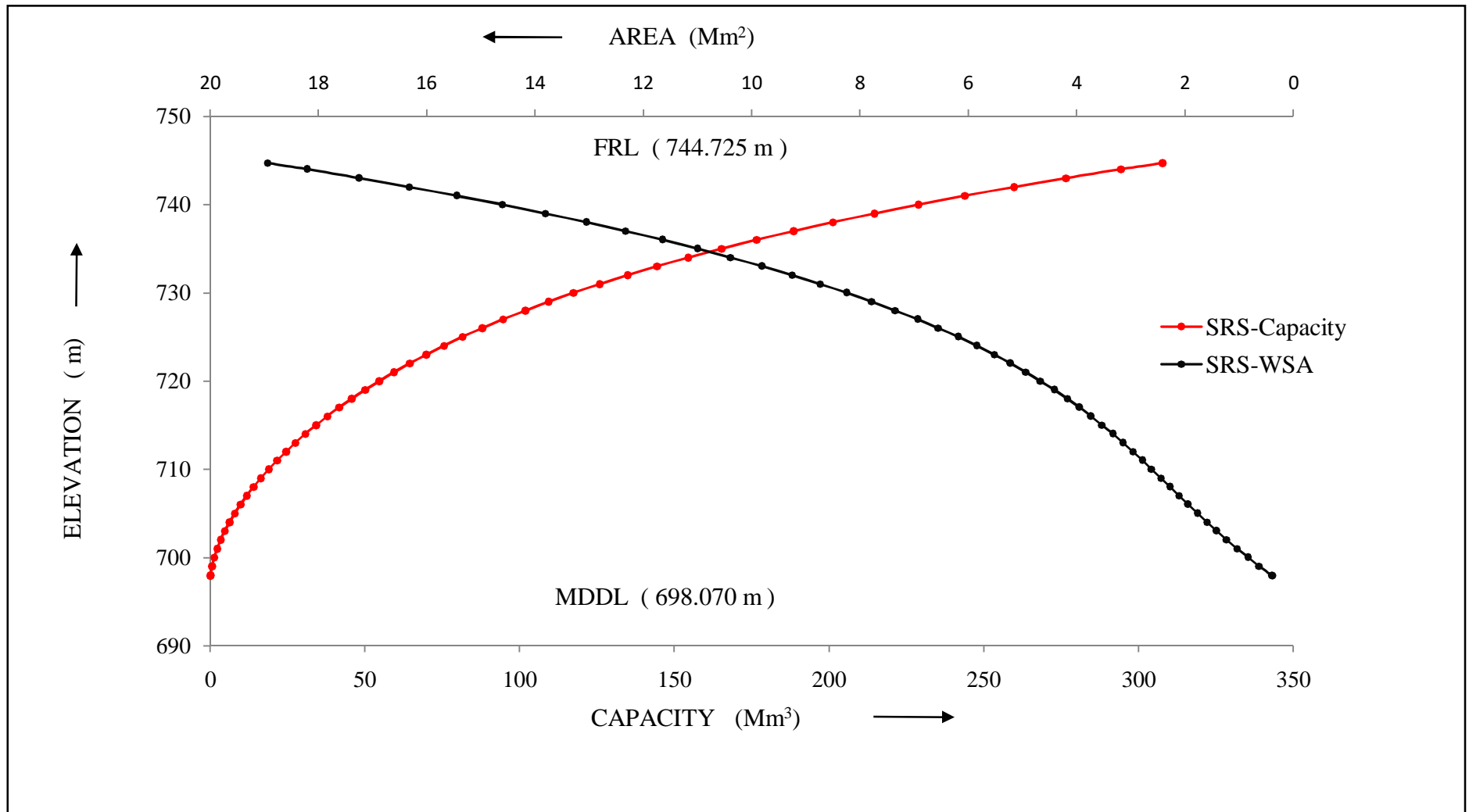


Figure 12 : Modified SRS Elevation-Area-Capacity curve for Bhandardara reservoir, Maharashtra

11.8 Comparison with earlier surveys

The comparison of water spread area obtained through remote sensing analysis with original surveyed data is given in Table 7.

Table 7 : Comparison of water spread areas of reservoir (Mm²)

Water elevation (m)	Original survey 1926	SRS survey 2018-19
MDDL 698.070	0.966	0.422
699.000	1.039	0.628
700.000	1.104	0.839
701.000	1.191	1.040
702.000	1.291	1.233
703.000	1.392	1.418
704.000	1.518	1.598
705.000	1.653	1.772
706.000	1.813	1.943
707.000	1.971	2.112
708.000	2.155	2.280
709.000	2.389	2.448
710.000	2.623	2.617
711.000	2.844	2.789
712.000	3.077	2.965
713.000	3.310	3.147
714.000	3.540	3.334
715.000	3.778	3.530
716.000	4.021	3.735
717.000	4.207	3.950
718.000	4.411	4.176
719.000	4.599	4.415
720.000	4.771	4.668
721.000	4.944	4.937
722.000	5.167	5.222
723.000	5.435	5.525
724.000	5.725	5.847
725.000	6.063	6.189

Water elevation (m)	Original survey 1926	SRS survey 2018-19
726.000	6.509	6.552
727.000	6.967	6.939
728.000	7.439	7.349
729.000	7.906	7.785
730.000	8.382	8.248
731.000	8.872	8.738
732.000	9.375	9.257
733.000	9.892	9.807
734.000	10.440	10.388
735.000	11.056	11.002
736.000	11.700	11.650
737.000	12.325	12.334
738.000	12.876	13.054
739.000	13.436	13.812
740.000	14.101	14.609
741.000	15.014	15.446
742.000	16.054	16.325
743.000	17.120	17.247
744.000	18.113	18.213
FRL 744.725	18.825	18.942

The comparison of present live storage capacity with original capacity is given in Table 8.

Table 8 : Comparison of live storage capacity of reservoir (Mm³)

Water elevation (m)	Original survey 1926	SRS survey 2018-19
MDDL 698.070	0.000	0.000
699.000	1.107	0.485
700.000	2.178	1.216
701.000	3.325	2.154
702.000	4.566	3.289
703.000	5.907	4.613
704.000	7.362	6.120
705.000	8.947	7.804
706.000	10.679	9.661
707.000	12.571	11.688
708.000	14.633	13.883
709.000	16.905	16.247
710.000	19.410	18.779
711.000	22.143	21.482
712.000	25.103	24.359
713.000	28.296	27.415
714.000	31.721	30.655
715.000	35.380	34.087
716.000	39.279	37.719
717.000	43.392	41.561
718.000	47.701	45.623
719.000	52.205	49.918
720.000	56.890	54.459
721.000	61.747	59.261
722.000	66.802	64.340
723.000	72.103	69.713
724.000	77.682	75.398

Water elevation (m)	Original survey 1926	SRS survey 2018-19
725.000	83.575	81.415
726.000	89.860	87.785
727.000	96.597	94.530
728.000	103.799	101.673
729.000	111.470	109.239
730.000	119.613	117.254
731.000	128.239	125.746
732.000	137.362	134.742
733.000	146.994	144.273
734.000	157.160	154.369
735.000	167.906	165.063
736.000	179.283	176.387
737.000	191.294	188.377
738.000	203.894	201.069
739.000	217.049	214.500
740.000	230.817	228.709
741.000	245.372	243.735
742.000	260.904	259.618
743.000	277.489	276.402
744.000	294.995	294.130
FRL 744.725	304.100	307.598

11.9 Field visit and ground truth

Field visit of the reservoir area has been carried out on 30th August 2019 for ground truth verification. Some predetermined ground truth points marked on the satellite image printouts along with their latitude and longitude values have been verified, with the help of GPS (Trimble Juno) receiver. Following officers were present during this visit.

Officers from Resources Engineering Center, MERI, Nashik

- i) Shri. S. A. Gaikwad, Sub Divisional Engineer
- ii) Mrs. P. K. Kedar, Assistant Engineer, Gr.-II
- iii) Mrs. A. P. Jadhav, Assistant Engineer, Gr.-II
- iv) Mrs. S. G. Kuwar, Assistant Engineer, Gr.-II

Team from Bhandardara reservoir project

- i) Shri. A. V. Deshmukh, Assistant Engineer, Gr-II

Latitude and longitude values of the reservoir components have been recorded during the field visit. Reservoir levels used in the present analysis have been confirmed in field visit. The reservoir level on the day of visit was observed 744.640 m. The Photographs of ground truth scenario are shown in Annexure III.

12. Results and Discussions

The loss in live storage capacity of the reservoir in remote sensing survey (2018-19) due to sedimentation since original survey (1926) is given in Table 9.

Table 9 : Live storage capacity loss due to sedimentation from original survey

Details	Original survey 1926	SRS survey 2018-19
Live capacity (MCM) at FRL 744.725 m	304.100	307.598
Loss in capacity (MCM)	-	(+) 3.498
% Live capacity loss (since 1926)	-	-
Annual % live capacity loss	-	-
% Live capacity loss between two consecutives surveys (of the original survey)	-	-
% Loss in live storage between the survey since impoundment.	-	-

The following observations are observed from the present study.

- Present live storage capacity (year 2018-2019) of Bhandardara reservoir is found out to be increased with respect to the design live storage. The present live storage is observed as 307.598 Mm³. Modified SRS elevation-area-capacity values are given in Table 6 and Figure 12.
- Regarding the increase in live storage capacity, It is to be mentioned that characteristic of the catchment of Bhandardara reservoir plays vital role. The total catchment area of Bhandardara at project site is about 122 sqkm. The area is situated in Western Ghat ranges draining towards east. The annual average rainfall in the catchment is 5460 mm. The catchment is hilly with steep valleys and thick forests. The area is surrounded by mountains on all the sides. These are all made up of basaltic rocks. It is to be mentioned that there is no soil mass observed in the catchment area due to predominantly compact basalt and amygdaloidal basalt.

13. Limitations

The sedimentation survey using Remote Sensing Technique has following limitations

- The remote sensing based capacity estimation works between the operating levels i.e. MDDL to FRL only. Thus changes can be estimated only in live capacity of reservoir.
- The cloud free satellite data throughout reservoir operation in single year is not possible. As such data from different years are selected.
- General error can creep in the identification of tail end of reservoir, particularly in the rainy season. Reservoir authorities have been consulted to remove this ambiguity.

14. Conclusions

Following conclusions can be drawn from the study:

- The live storage capacity of Bhandardara reservoir is 307.598 Mm³ in year 2018-19.
- In capacity no loss in live storage is observed in a period of 93 years since first impounding in 1926.
- It is to be mentioned that Hydrographic survey is recommended.

References

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Central Water Commission, Technical reports on reservoir capacity estimation using satellite remote sensing for different reservoirs. RS Directorate, New Delhi.

R. V. Panse., R. V. Shrigiriwar M. B. Nakil, M. M. Kulkarni, S. A. Gaikwad, (2015), Sedimentation assessment of Krishnagiri reservoir, Tamil Nadu through satellite remote sensing, Technical Report, MERI, Nashik and CWC, Delhi.

Varshney, R.S., (1997), Impact of siltation on the useful life of large reservoirs, State of art report of INCOH, No. INCOH/SAR-11/97, NIH, Roorkee.

Annexure I

Salient Features

A	Location		
	Village	:	Shendi
	Taluka	:	Akole
	District	:	Ahmednagar
	State	:	Maharashtra
	Latitude	:	19 ⁰ 32' 30" N
	Longitude	:	73 ⁰ 45' 47" E
	River	:	Pravara
B	Hydrology		
	Catchment area	:	122.000 sq km
C	Dam		
	Type of dam	:	Masonry Dam (Gravity)
	Length of dam	:	507.000 m
	Height of the dam	:	82.320 m
D	Capacity of Dam		
	Gross storage capacity at FRL	:	312.600 Mm ³
	Dead storage capacity	:	8.500 Mm ³
	Live capacity	:	304.130 Mm ³
E	Spillway	:	
	Type of spillway	:	Gated Waist wear Open Bar
	Design spillway discharge capacity	:	1516.300 m ³ /s 2550.000 m ³ /s
	No., Size of spillway	:	2 Nos., -- 12.500 m x 7.930 m 170.000 m
F	Reservoir Data		
	Top of dam	:	746.035 m
	Maximum water level	:	746.035 m
	Full reservoir level	:	744.725 m
	Spillway crest level	:	736.800 m
	Minimum draw down level	:	698.070 m
G	Year of completion	:	1926

Annexure II

Reservoir Levels Pertaining to Cloud Free Satellite Data

Path/Row - 95 / 59	Gross storage capacity at FRL -	312.600 Mm ³
FRL - 744.725 m	Design live storage	- 304.100 Mm ³
MDDL - 698.070 m	Dead storage capacity	- 8.500 Mm ³

Date of pass	Reservoir level (m)	Capacity covered (Mm ³)
1	2	3
11-Jun-2019	700.680	11.440
18-May-2019	709.120	25.680
9-May-2016	710.990	30.582
27-Apr-2016	715.120	44.315
24-Mar-2019	720.710	67.330
16-May-2017	724.520	86.649
07-Mar-2019	726.070	96.361
23-Feb-2019	729.270	119.071
29-Apr-2018	731.800	139.884
29-Mar-2017	735.510	174.402
24-Mar-2018	738.940	213.309
28-Feb-2018	741.800	255.642
31-Oct-2017	744.725	312.600
Variation in capacity		(312.60 - 11.44) = 301.16
% variation of live storage		(301.16 / 304.10)*100 = 99.03 %

Ground Truth Scenario



Dam view



Dam downstream side



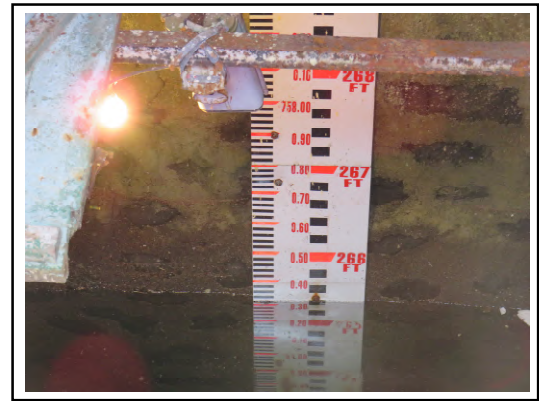
Radial gate



Overflow section



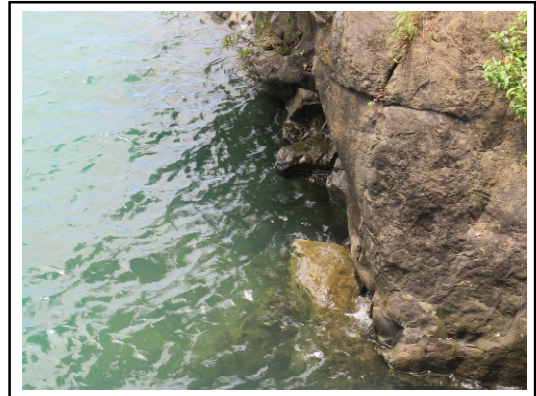
Pravara river (down stream)



Water gauge



Submerged area



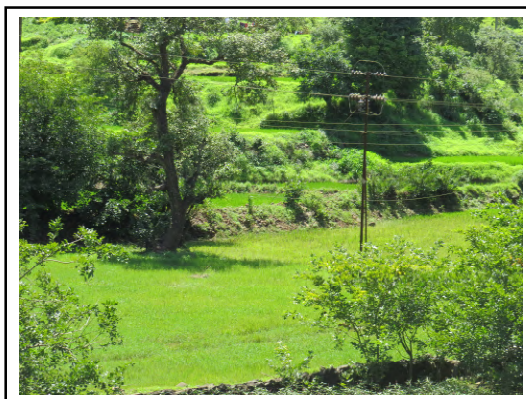
Solid rocks in submergence



Mountains around submergence



Hilly area around submergence



Crops in command



Ground truth team

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