उपग्रह दूरस्थ संवेदन द्वारा
सिपु जलाशय, गुजरात का अवसादन आंकलन

Sedimentation Assessment of Sipu Reservoir, Gujarat, through Satellite Remote Sensing

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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.

(Amrendra Kumar Singh)
Chief Engineer (EMO)
Central Water Commission

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 Sipu 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. J. D. Mistry, Superintending Engineer , Sujalam Sufalam Circle No.2, GWRDC Building Opp- Ganpat University, Kherva, Dist-Mehsana ,Gujarat the keen interest shown in the work. We are also thankful to Shri. R. N. Ninama, Executive Engineer, Sipu Project Division, Shri. V. T. Chauhan, Deputy Engineer, Shri. S. M. Bihari, Assistant Engineer-II, of Sipu Project Division, Gujarat for supplying all relevant data required for the present analysis.

PROJECT TEAM

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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
Mm^2	Million square meter
Mm^3	million cubic meters
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 numbers 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 Sipu Reservoir, Gujarat, India.

Present study aims in updating the elevation-area-capacity curve of Sipu Reservoir, Gujarat, and finding the capacity loss due to sedimentation in live storage. For carrying out the analysis, Resourcesat 2 and Resourcesat 2A LISS III data with 23.5 m resolution have been used. Satellite data for ten passes falling between MDDL (176.400 m) and FRL (186.430 m) are used for the analysis.

The Sipu dam is located on the Sipu River. The dam site is located near Bhakodar village in taluka Dantiwada, Banaskantha district. The project has a designed gross capacity of 177.800 Mm^3, with live capacity of 156.000 Mm^3. As per hydrographic survey year 2007-08, the gross capacity was found out to be 161.430 Mm^3 with live capacity of 145.370 Mm^3.The field authorities has accepted the hydrographic study done by Gujarat Engineering Research Institute (GERI).

The present study covers 100 % of live storage i.e.156.000 Mm^3. This study reveals that the present live capacity of reservoir is reduced by 19.093 Mm^3 witnessing a loss of 12.239 % in a period of 26 (1992-2018) years in live storage zone. This amounts to 0.471% loss per annum in live storage since the impoundment.

SEDIMENTATION ASSESSMENT OF SIPU RESERVOIR, GUJARAT, 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 Sipu reservoir, Gujarat by Central Water Commission, New Delhi.

2. Sources and Mechanism of Sedimentation

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. Channelization 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.

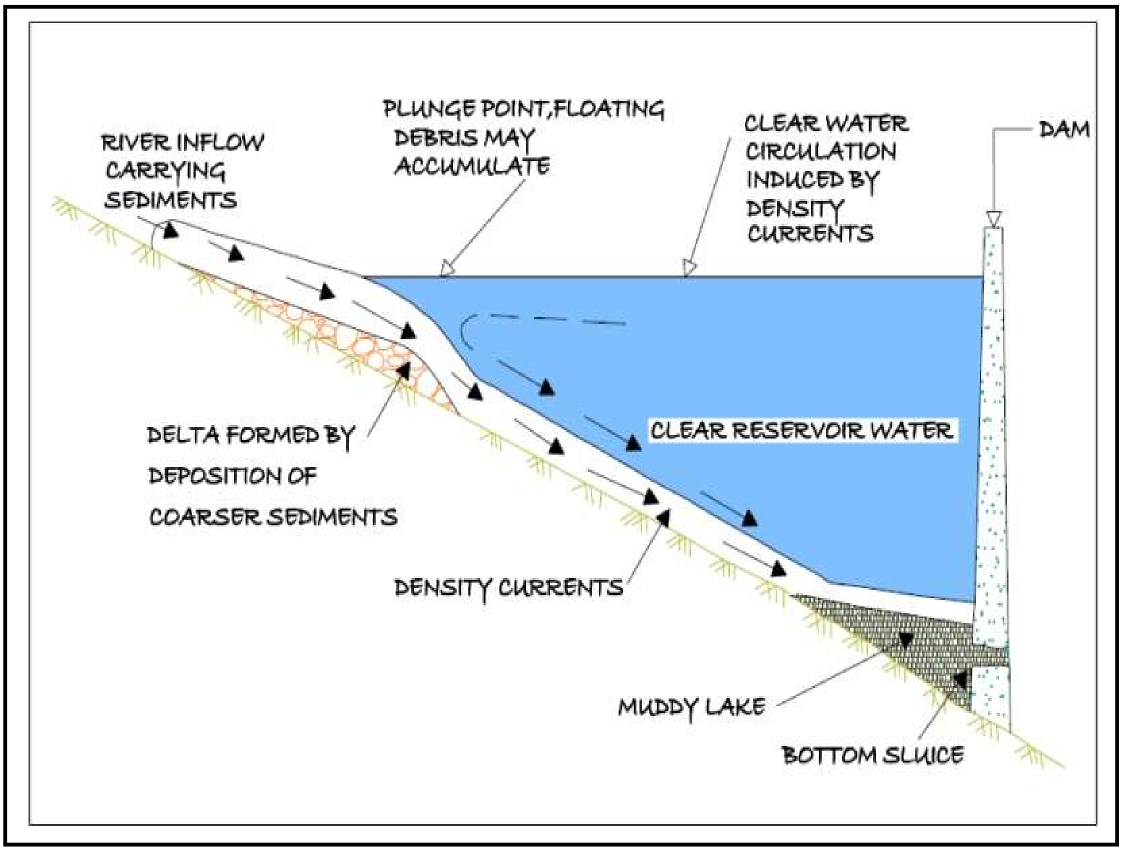


Figure 1 : Conceptual sketch of density currents in a reservoir

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 depositions 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.

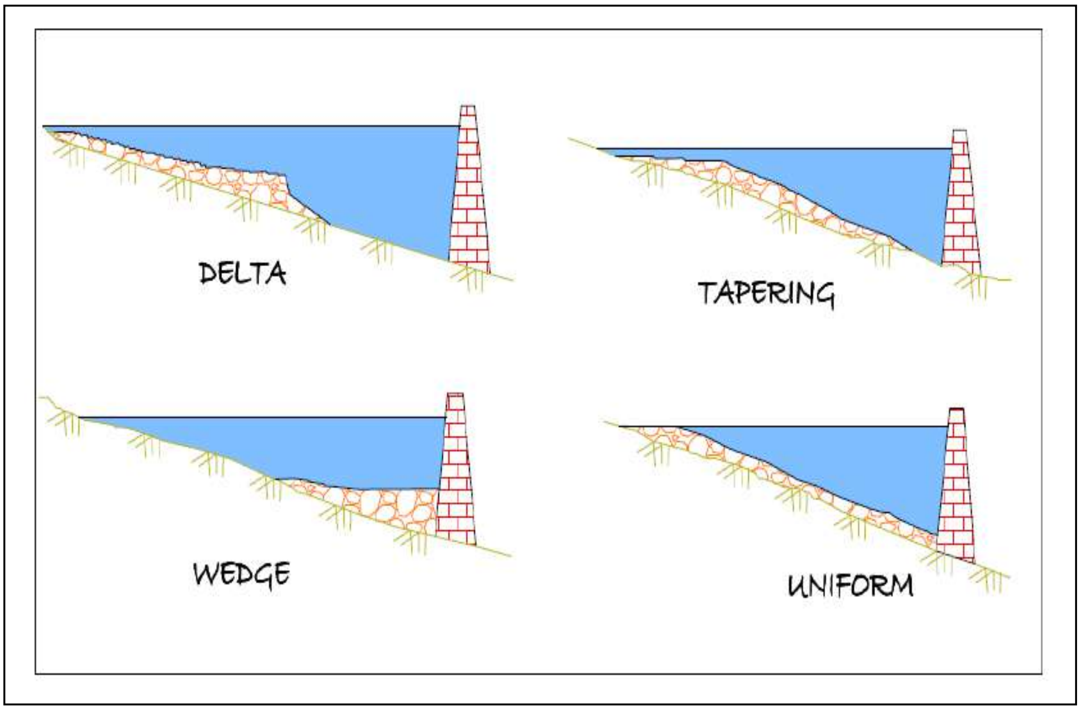


Figure 2 : Longitudinal Patterns of sediment deposition in reservoirs.

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 function 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.

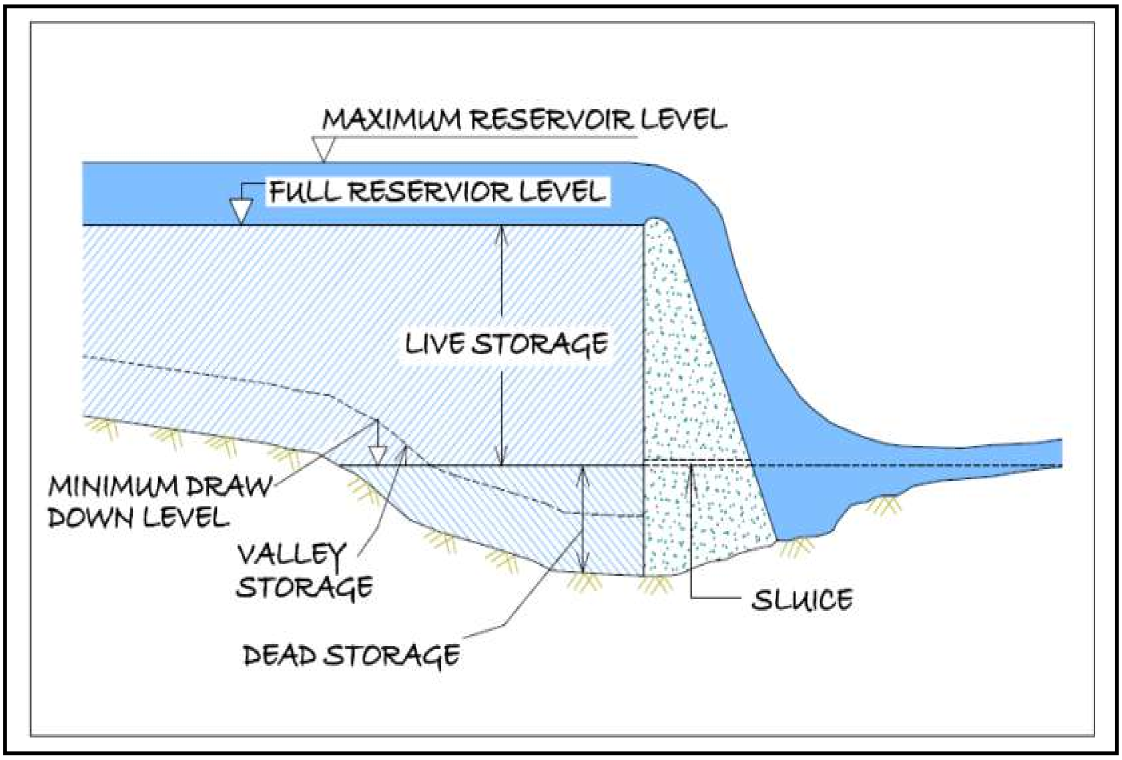


Figure 3 : Conceptual sketch of different levels in a reservoir

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 Resoucesat 2 and Resoucesat 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 Sipu 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 Sipu reservoir.

(ii) Estimation of live storage loss due to sedimentation in Sipu reservoir.

6. Study Area

The Sipu dam is located near Bhakodar village in Dantiwada taluka, Banaskantha district, on the Sipu River. The dam site is located at 24^0 22’ 30” N latitude and 72^0 15’ 00” E longitude. The location of the dam is shown in Figure 3 as Index Map. The Sipu dam serves the multipurpose of irrigation, Water supply and Fisheries. The total catchment area at the dam site is 1222.000 sq km. and catchment area laying in Rajasthan is 970.000 sq km and catchment area laying in Gujarat is 252.000 sq km. The dam was completed in the year 1992. The FRL and HFL of the reservoir are at a level of 186.430 m and 186.480 m respectively. The dead storage and live storage capacity of Sipu dam are 21.800 Mm^3 and 156.000 Mm^3 respectively. The spillway crest level of dam is 178.157 m.

There is only one main canals taking off from the reservoir. The length of right main canal is 21.630 km. Salient features of Sipu project are given in Annexure (I).

7. Previous Surveys

Previous hydrographic survey has been carried out in year 2007. The results of previous surveys are summarized in Table 1.As field authority has accepted the 2007 survey results and being used in water planning, hence this report deals with the storages of 2007 hydrographic survey.

Table 1 : Summary of previous surveys

Details of survey	Live capacity (Mm^3)	Cumulative loss	Cumulative % loss
Original survey (1992)	156.000	-	-
Hydrographic survey (GERI) (2007-2008)	145.370	10.630	6.820

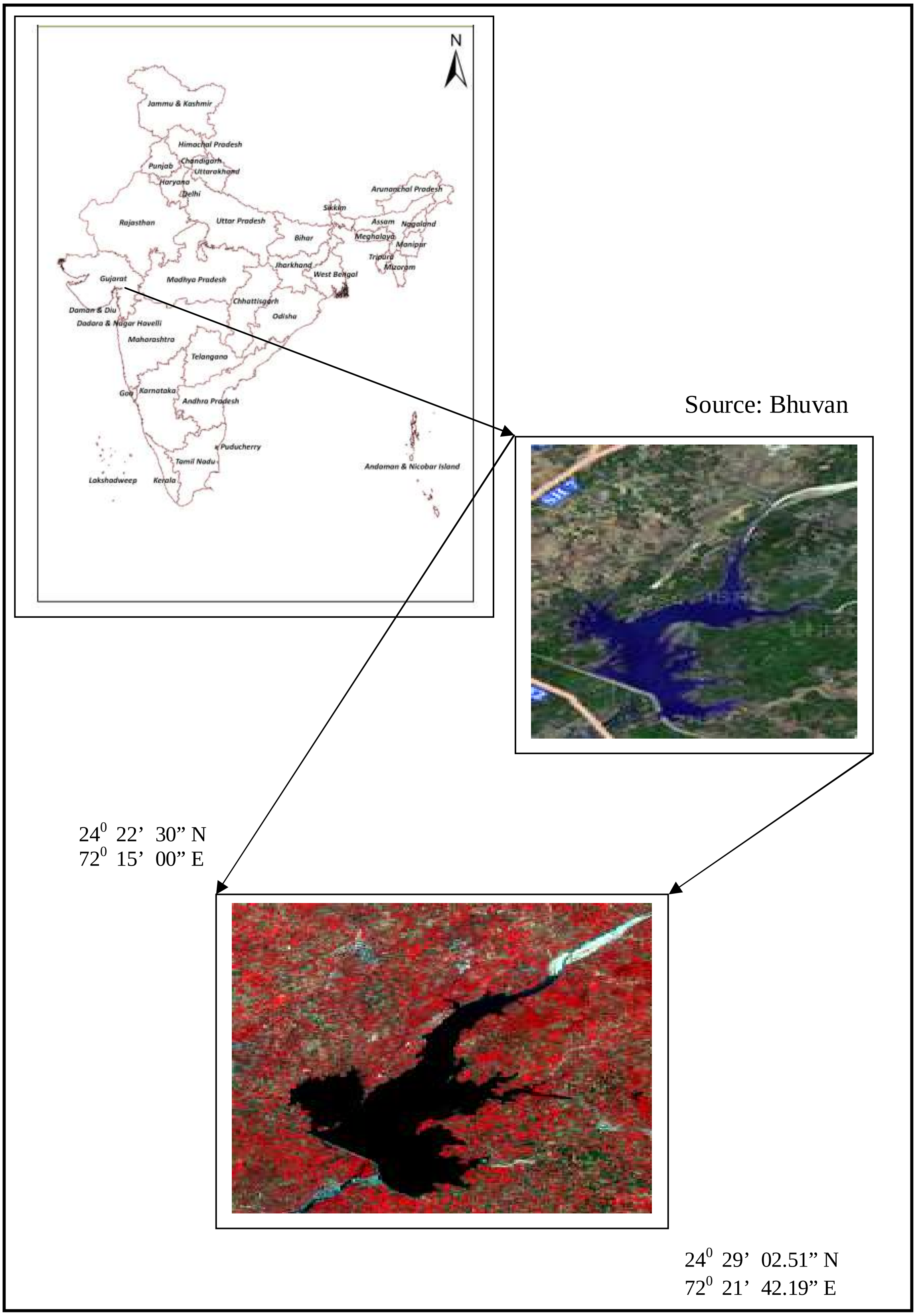


Figure 4 : Index map of Sipu reservoir, Gujarat

8. Approach of Present Study

Remote sensing technique is utilized to assess the sedimentation between operating levels of reservoir. This operating range between MDDL (176.400 m) and FRL (186.430 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	2016-2017	175.730	180.760	5.030
2	2017-2018	182.070	185.760	3.690
3	2018-2019	-----	177.160	----

The information reveals that in the water year 2017-2018, reservoir was filled up to 185.760 m near to FRL 186.430 m while it got depleted R.L 175.730 m below the MDDL 176.400 m in 2016-2017. For present study, four images from water year 2016-2017, five images from water year 2017-2018 and one image from water year 2018-2019 have been used. The year of survey of present study is treated as year 2017-2018.

9. Data

9.1 Field data

Following data set was obtained from Executive Engineer, Sipu Project Division, Sinchai Bhavan, Palanpur for Sipu 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

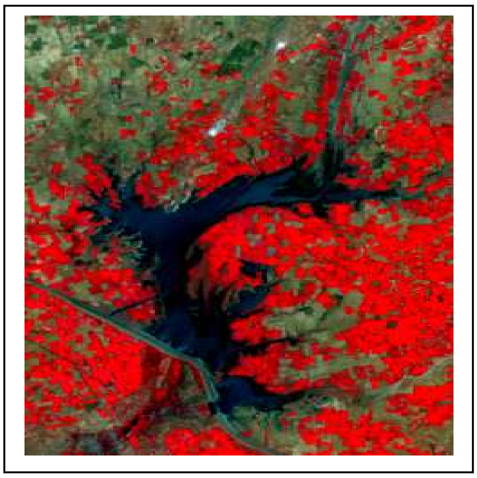
v) Reservoir levels for given dates of satellite pass.

9.2 Satellite data

Resourcesat 2 and Resourcesat 2A LISS III images of 23.5 m resolution having Path 92, Row 54 have been used in present analysis. The FCC of the images are as given in Figure 4. The dates of satellite pass of selected images and corresponding reservoir levels are given in Table 3.

Table 3 : Details of satellite data

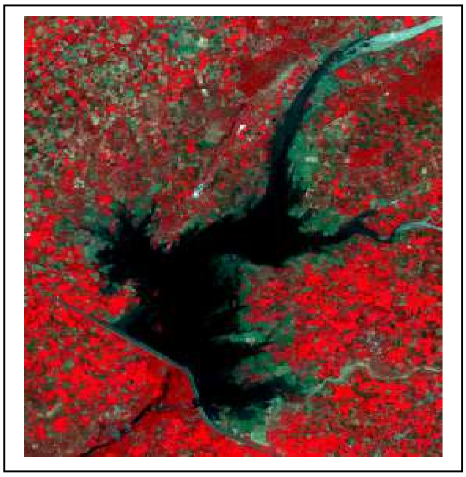
Sr. No.	Date of pass	Elevation (m)
1	16-Oct-17	185.760
2	27-Dec-17	184.850
3	09-Mar-18	183.950
4	26-Apr-18	182.910
5	20-May-18	182.070
6	29-Sep-18	180.760
7	27-Sep-16	179.550
8	20-Dec-16	178.310
9	08-Feb-19	177.160
10	25-May-17	175.730



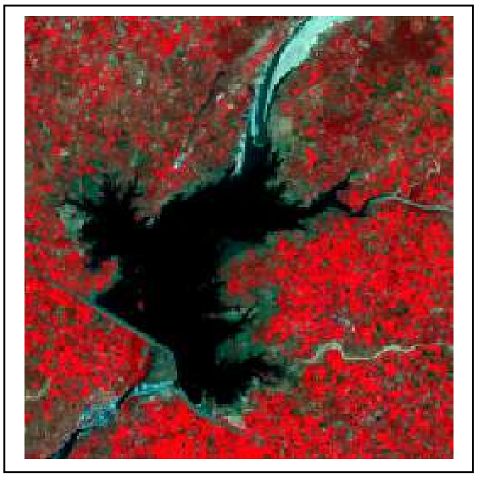
25- May- 2017 (175.730 m)

08- Feb- 2019 (177.160 m)

20 - Dec - 2016 (178.310 m)



27- Sept- 2016 (179.550 m)



29- Sep- 2018 (180.760 m)

20- May -2018 (182.070 m)

Figure 5 : FCC’s of Sipu reservoir, Gujarat

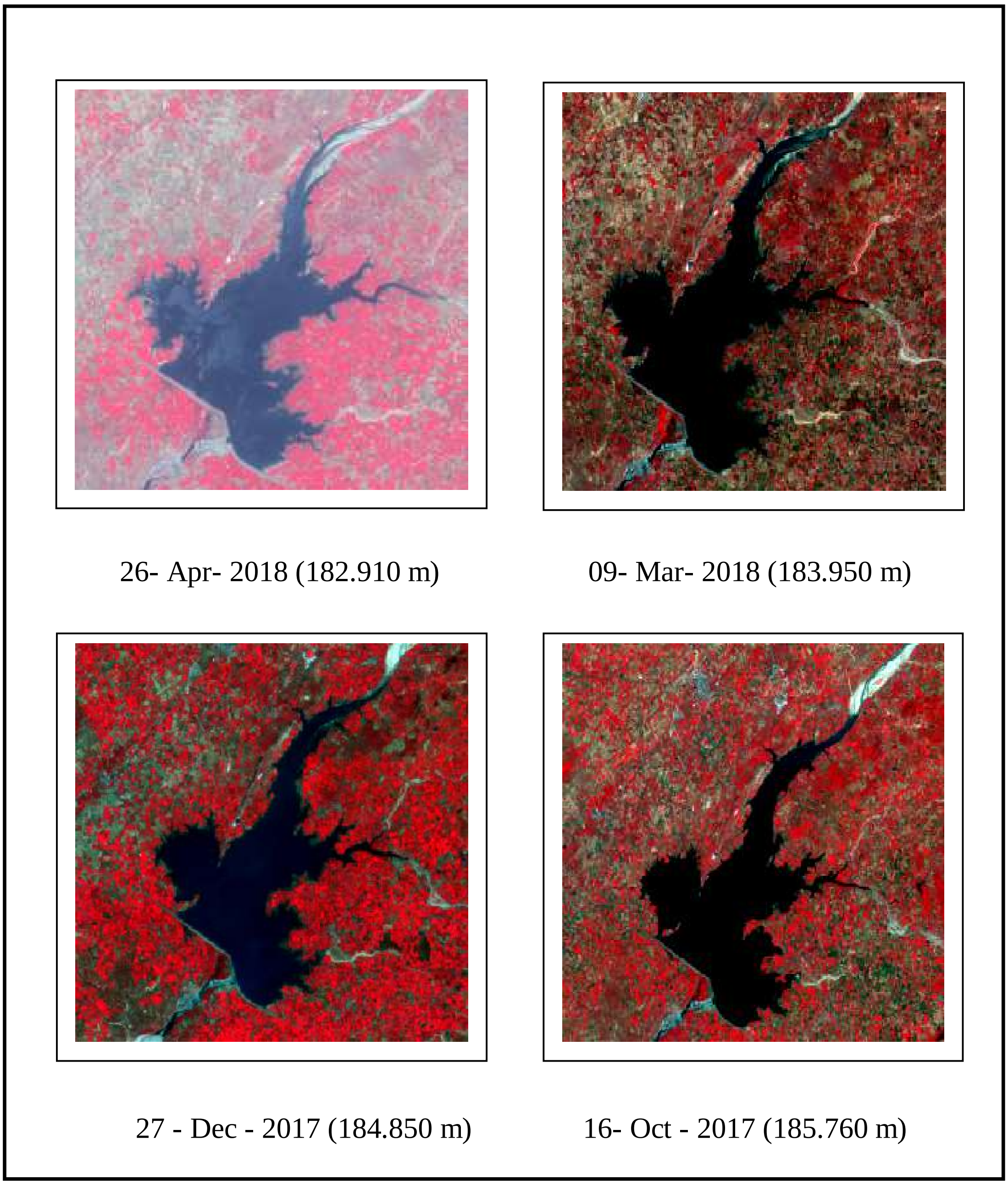


Figure 5 : FCC's of Sipu reservoir, Gujarat

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 Sipu 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 175.730 m as against MDDL (176.400 m). The maximum level covered in the present study is 185.760 m, which is near to FRL (186.430 m). Variation in the study level is (185.760 – 175.730) = 10.030 m. The difference between FRL and MDDL is (186.430 – 176.400) = 10.030 m.

In the present study, storage of 131.064 Mm^3 has been covered as against total live capacity of 145.370 Mm^3. Thus the percentage live storage covered by this study is 90.158 %. (Annexure II)

Statement giving cloud free dates of satellite pass, reservoir levels, areas and capacities for the Sipu 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

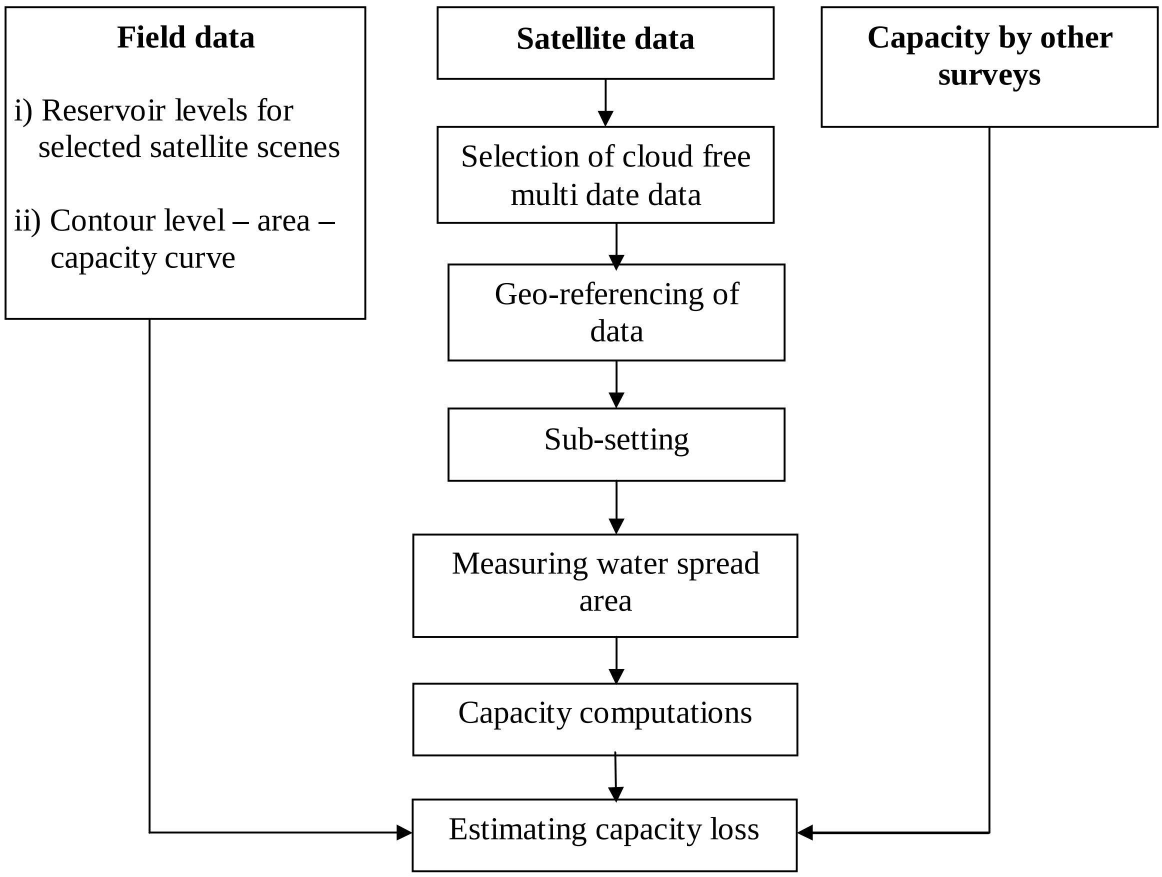


Figure 6 : Flow chart showing methodology for reservoir capacity estimation

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 Sipu reservoir

Date of pass	Minimum value	Maximum value
16-Oct-17	- 0.0429	0.2328
27-Dec-17	0.0472	0.3605
09-Mar-18	0.0274	0.2851
26-Apr-18	-0.1048	0.0975
20-May-18	-0.0969	0.0696
29-Sep-18	-0.0536	0.3112
27-Sep-16	-0.0589	0.1663
20-Dec-16	0.1177	0.6540
08-Feb-19	-0.0626	0.2028
25-May-17	-0.1451	0.0244

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)
16-Oct-17	185.760	23.560
27-Dec-17	184.850	21.290
09-Mar-18	183.950	18.901
26-Apr-18	182.910	16.278
20-May-18	182.070	14.296
29-Sep-18	180.760	11.436
27-Sep-16	179.550	9.528
20-Dec-16	178.310	7.372
08-Feb-19	177.160	5.184
25-May-17	175.730	3.760

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 second 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

$$V = H / 3 * (A_1 + A_2 + SQRT (A_1 * A_2)).$$

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

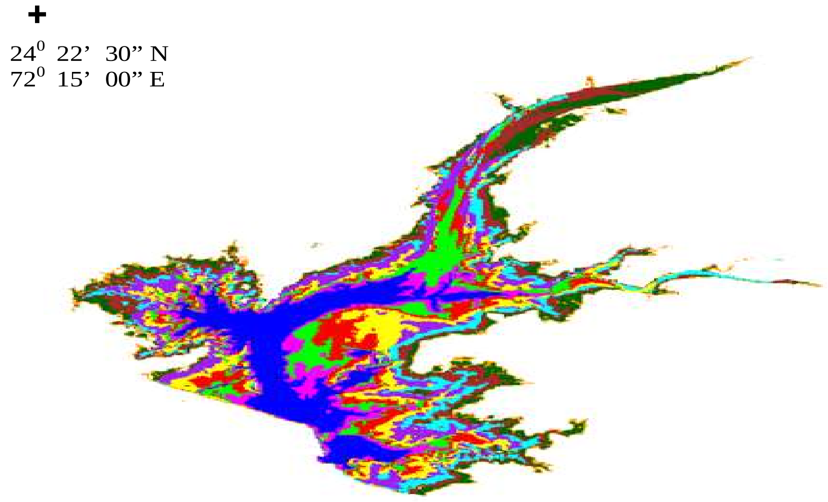
H is the elevation difference, $H = (h_1 - h_2)$

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 (2017-18)	Cumulative capacity Mm^3 (2017-18)
MDDL 176.400	4.471	0.000
177.000	5.268	2.918
177.160	5.490	3.779
178.000	6.727	8.901
178.310	7.213	11.062
179.000	8.352	16.427
179.550	9.316	21.283
180.000	10.142	25.660
180.760	11.613	33.921
181.000	12.098	36.766
182.000	14.218	49.910
182.070	14.373	50.911
182.910	16.291	63.781
183.000	16.504	65.257
183.950	18.828	82.027
184.000	18.955	82.972
184.850	21.168	100.015
185.000	21.571	103.221
185.760	23.670	120.406
186.000	24.352	126.168
FRL 186.430	25.599	136.907



Legand		
Colour	Date of Image	Area (Mm^2)
Blue	25- May -2017	3.760 Mm^2
Magenta	08- Feb -2019	5.184 Mm^2
Green	20- Dec- 2016	7.372 Mm^2
Red	27- Sep -2016	9.528 Mm^2
Yellow	29- Sep -2018	11.436 Mm^2
Purple	20- May -2018	14.296 Mm^2
Cyan	26- Apr -2018	16.278 Mm^2
Maroon	09- Mar -2018	18.901 Mm^2
Dark green	27- Dec- 2017	21.290 Mm^2
Orange	16- Oct – 2017	23.560 Mm^2

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 hydrographic survey 2007 and present surveys carried out for Sipu reservoir are shown in Figure 10 which is based on Table 7. The elevation-capacity curve drawn through hydrographic survey 2007 and present surveys carried for the Sipu 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.

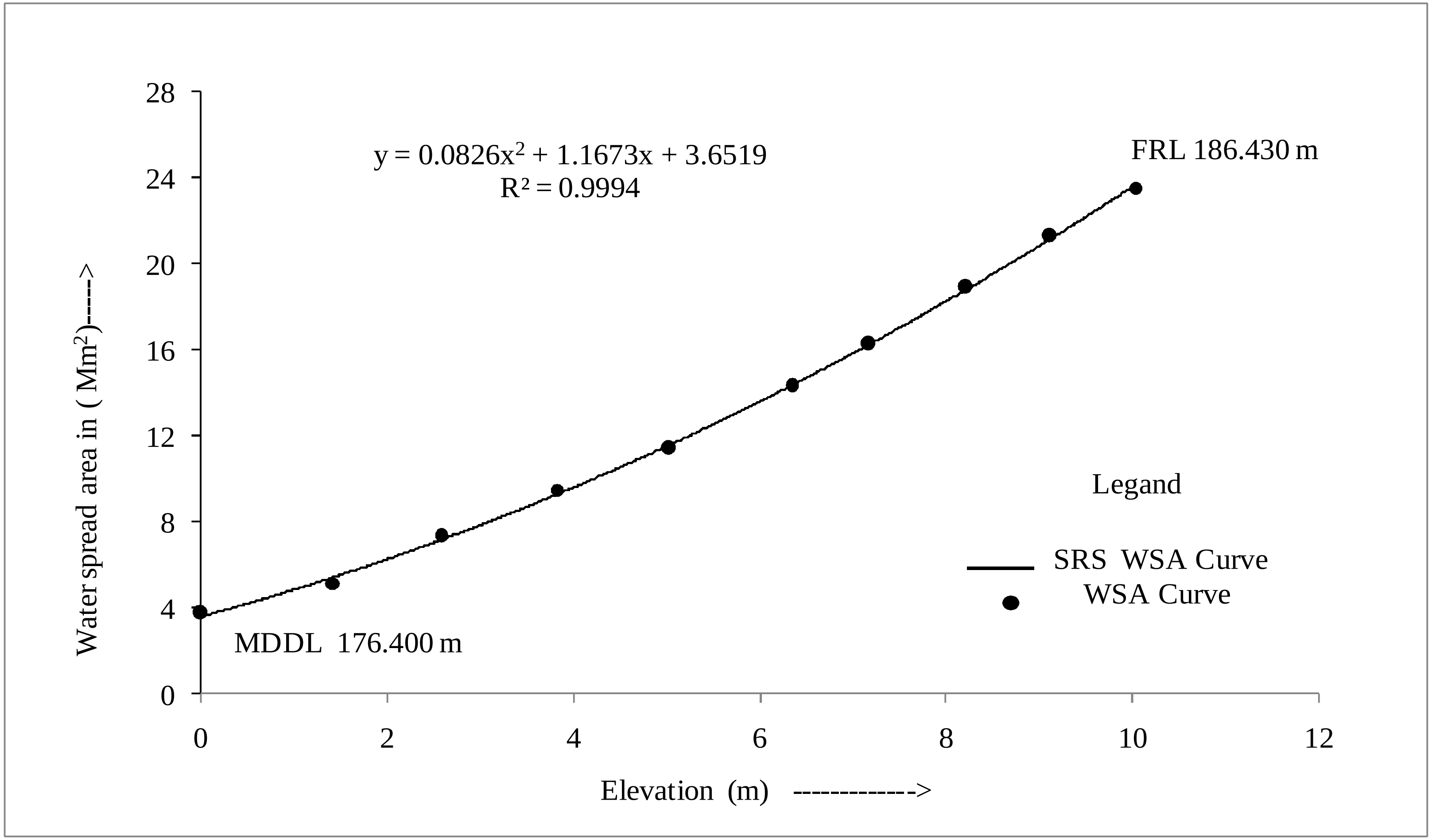


Figure 8 : SRS Elevation-Area curve for Sipu reservoir, Gujarat

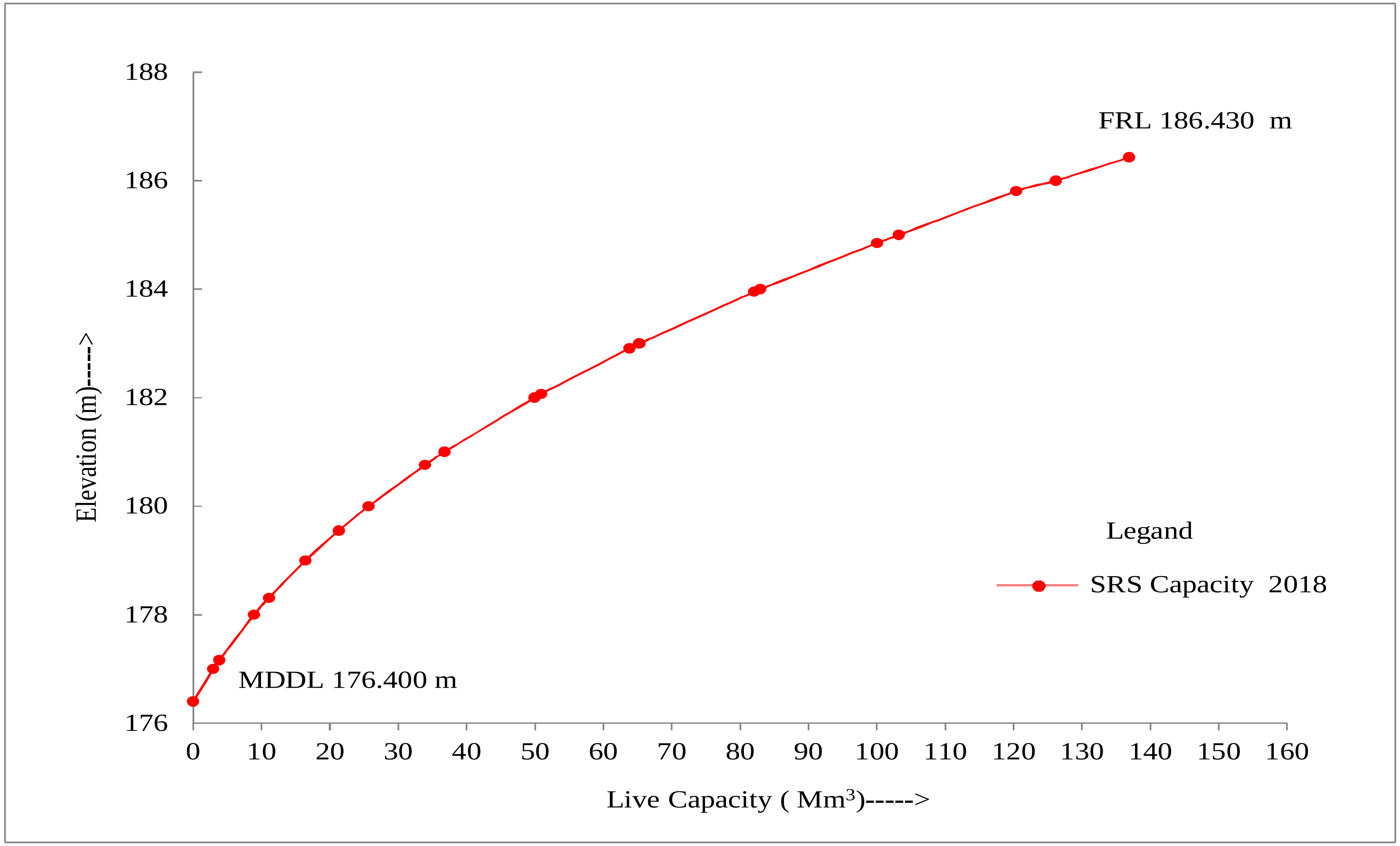


Figure 9 : SRS Elevation-Capacity curve for Sipu reservoir, Gujarat

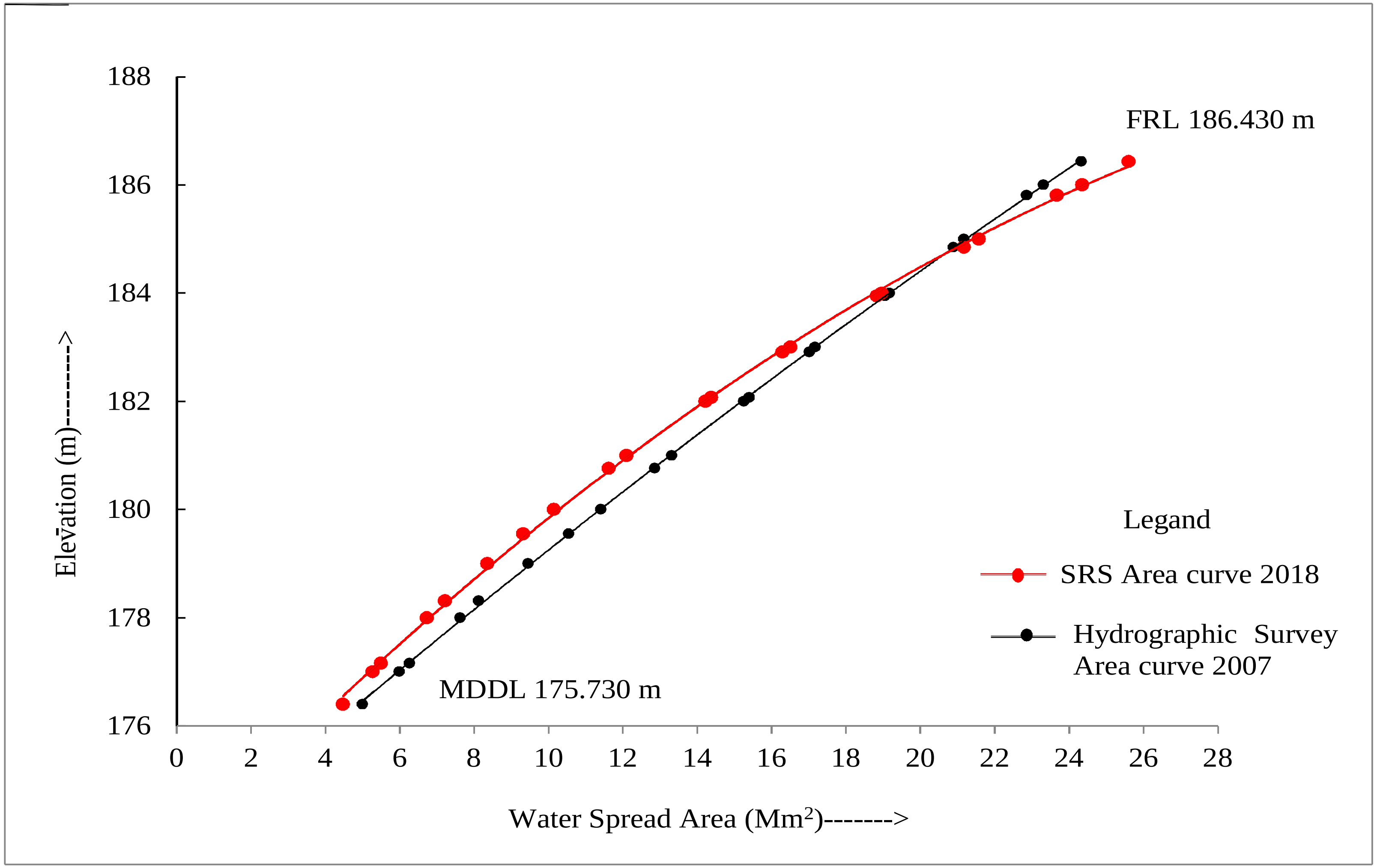


Figure 10 : Elevation - Area curve for different years for Sipu reservoir, Gujarat

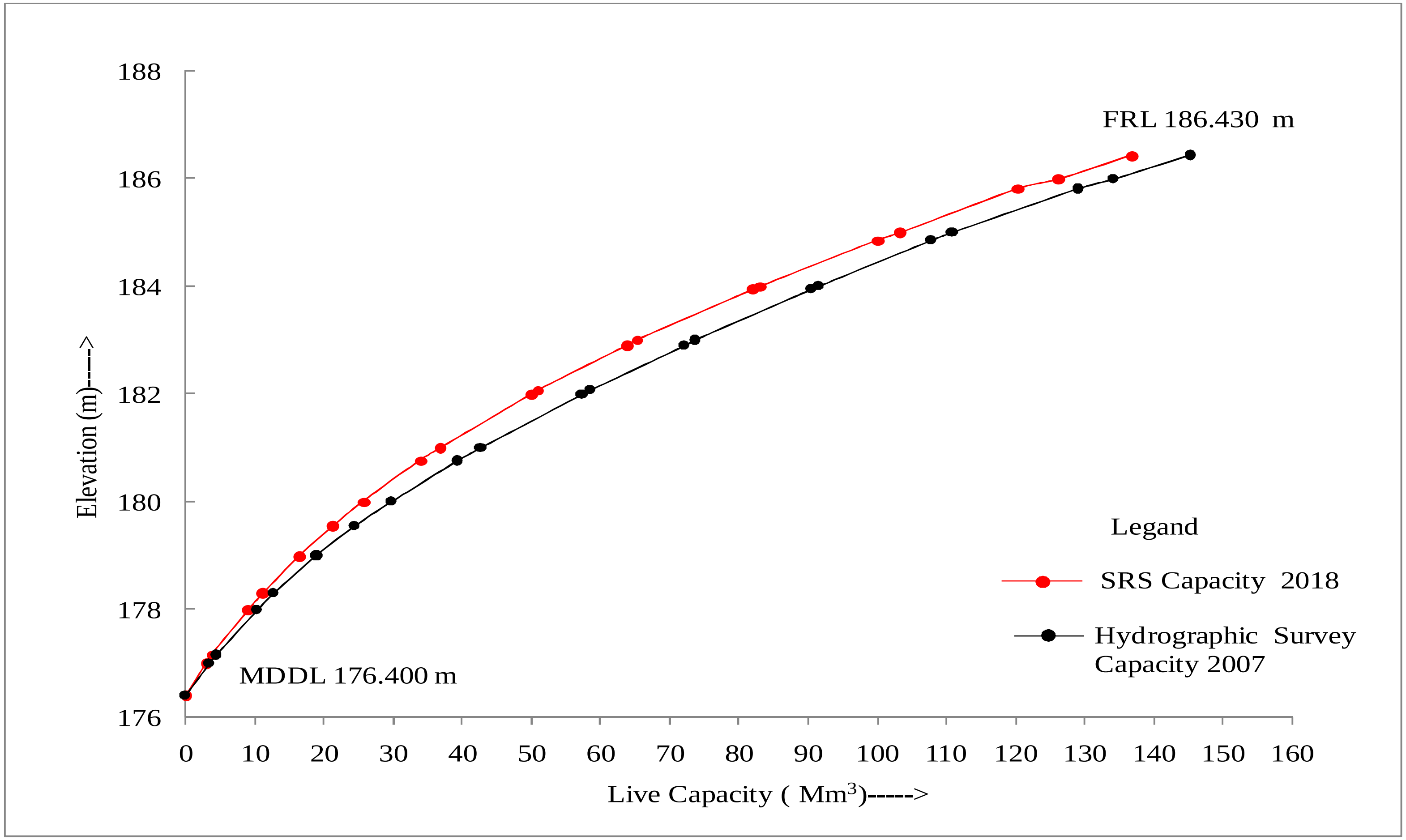


Figure 11 : Elevation - Capacity curve for different years for Sipu reservoir, Gujarat

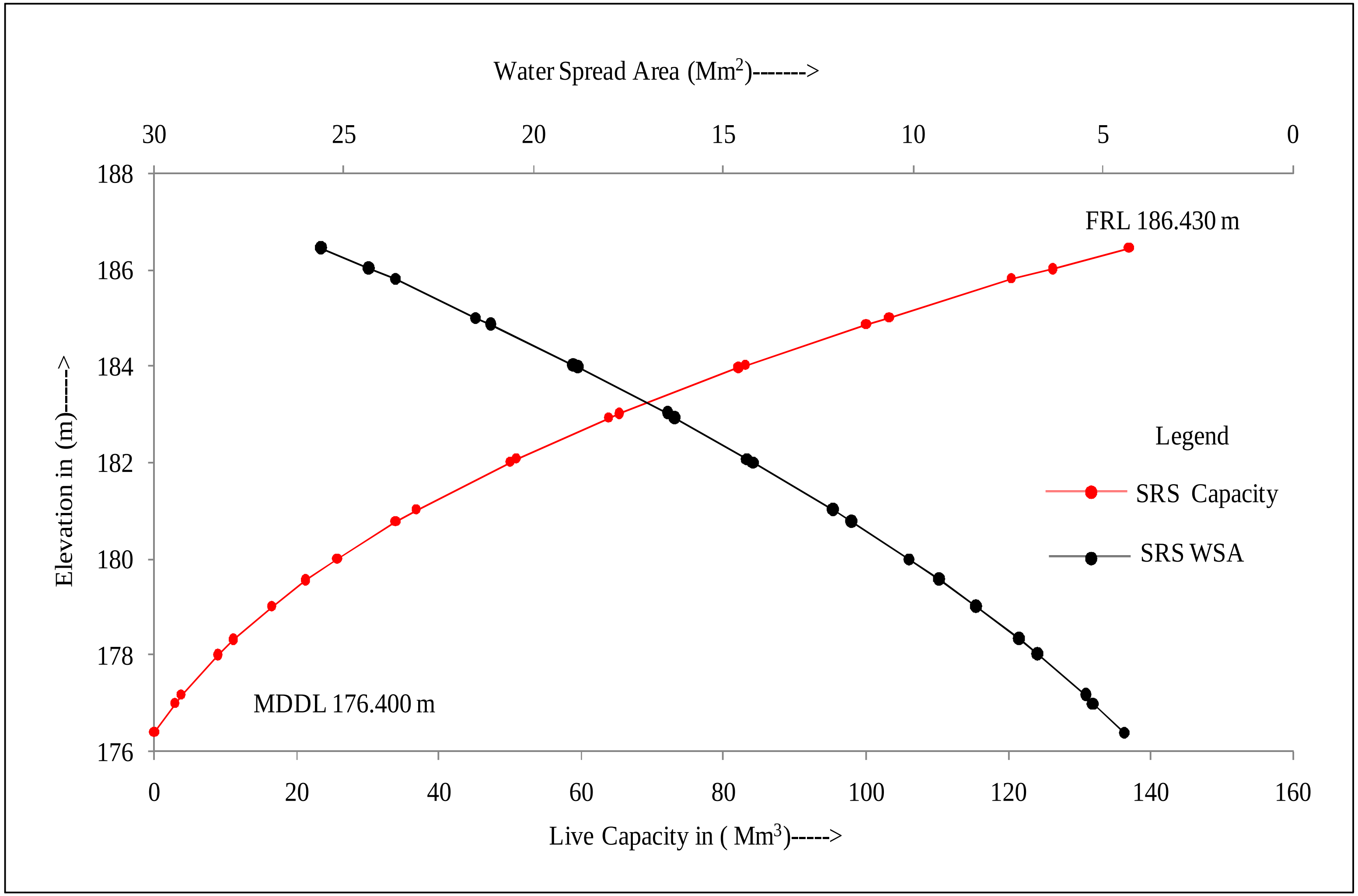


Figure 12: Modified SRS Elevation- Area- capacity curve for Sipu reservoir, Gujarat

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 (Mm^2)

Water elevation m	Hydrographic survey 2007	SRS survey 2017-18
MDDL 176.400	4.996	4.471
177.000	5.993	5.268
177.160	6.260	5.490
178.000	7.626	6.727
178.310	8.122	7.213
179.000	9.451	8.352
179.550	10.541	9.316
180.000	11.412	10.142
180.760	12.863	11.613
181.000	13.314	12.098
182.000	15.257	14.218
182.070	15.396	14.373
182.910	17.018	16.291
183.000	17.174	16.504
183.950	19.058	18.828
184.000	19.167	18.955
184.850	20.888	21.168
185.000	21.167	21.571
185.810	22.865	23.670
186.000	23.314	24.352
FRL 186.430	24.331	25.599

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

Table 8 : Comparison of live storage capacity of reservoir (Mm^3)

Water elevation m	**Hydrographic survey 2007**	**SRS survey 2017-18**
MDDL 176.400	0.000	0.000
177.000	3.474	2.918
177.160	4.407	3.779
178.000	10.317	8.901
178.310	12.675	11.062
179.000	19.021	16.427
179.550	24.523	21.283
180.000	29.787	25.660
180.760	39.361	33.921
181.000	42.666	36.766
182.000	57.390	49.910
182.070	58.472	50.911
182.910	72.198	63.781
183.000	73.722	65.257
183.950	90.586	82.027
184.000	91.507	82.972
184.850	107.906	100.015
185.000	110.932	103.221
185.810	129.171	120.406
186.000	134.133	126.168
FRL 186.430	145.366	136.907

11.9 Field visit and ground truth

Field visit of the reservoir area has been carried out on 07th November 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. M. M. Kulkarni, Executive Engineer

Team from Sipu reservoir project

i) Shri. R. N. Ninama, Executive Engineer.

ii) Shri. V.T. Chauhan, Deputy Engineer.

iii) Shri. S.M. Bihari, Assistant Engineer-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 177.120 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 (2017-2018) due to sedimentation since, design survey (1992) and hydrographic survey (2007) is given in Table 9.

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

Details	Design Survey 1992	Hydrographic Survey 2007	SRS survey 2017-18
Live capacity (MCM) at FRL 186.430 m	156.000	145.370	136.907
Loss in capacity (MCM)	-	10.630	19.093
% Live capacity loss (since 1992)	-	6.814	12.239
Annual % live capacity loss	-	0.454	0.471
% Live capacity loss between two consecutive surveys (of the original capacity)	-	6.814	5.425
% Loss in live storage between the survey since impoundment	-	6.814	12.239

The following observations are recorded from the present study.

- Present live capacity (year 2017-2018) of Sipu reservoir is found as 136.907 Mm^3. Modified SRS elevation-area-capacity values are given in Table 6 and Figure 12.

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 present live storage capacity of sipu reservoir is 136.907 Mm^3 in year 2017-18.
- Capacity loss of 12.239 % in live storage is observed in a period of 26 years since design survey in 1992.
- Capacity loss of 6.816 % in live storage zone is observed in a period of 15 years in 1^{st} hydrographic survey in 2007.The field authority has accepted and implemented the hydrographic survey in 2007. As, field authority is currently using the storages of hydrographic survey 2007 for water planning, therefore this survey (2017-18) is compared with hydrographic survey (2007) for deriving figure 10 and 11 as per Table 7 and 8.
- Annual live capacity loss works out to 0.471 % since design survey in 1992.

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Annexure I

Salient Features

A	**Location**			
	Name of Reservoir		Sipu Reservoir	
	Village	:	Bhakodar	
	Taluka	:	Dantiwada	
	District	:	Banaskantha	
	State	:	Gujarat	
	Longitude	:	24^0 22’ 30” N	
	Latitude	:	72^0 15’ 00” E	
	River	:	Sipu	
B	**Hydrology**			
	Catchment area	:	1222.000 sq km	
C	**Masonry and Earthen Dam**			
	Length of dam	:	360.000 m	
	Height of the dam	:	39.650 m	
D	**Capacity of Dam**		**As per Original**	**As per Hydrographic survey 2007**
	Gross storage capacity at FRL	:	177.800 Mm^3	161.430 Mm^3
	Dead storage capacity	:	21.800 Mm^3	16.060 Mm^3
	Live capacity	:	156.000 Mm^3	145.370 Mm^3
	Design spillway discharge capacity	:	7015.000 m^3/s	
	Type of spillway	:	Ogee	
	Type, No., Size of spillway	:	Lift gates, 12 Nos., 12.500 m x 8.230 m	
E	**Reservoir Data**			
	Top of dam	:	192.000 m	
	Maximum water level	:	186.480 m	
	Full Reservoir level	:	186.430 m	
	Spillway crest level	:	178.157 m	
	Minimum draw down level	:	176.400 m	
	Year of Impounding	:	1992	

Annexure II

Reservoir Levels Pertaining to Cloud Free Satellite Data

Path/Row - 92 / 54 / 00

FRL – 186.430 m

MDDL - 176.400 m

As per Hydrographic survey 2007, Gross storage capacity at FRL-161.430 Mm^3

As per Hydrographic survey 2007, Live storage – 145.370 Mm^3

As per Hydrographic survey 2007, Dead storage capacity – 16.060 Mm^3

Date of pass	**Reservoir level (m)**	**Capacity covered (Mm^3)**
1	2	3
16-Oct-17	185.760	144.172
27-Dec-17	184.850	123.969
09-Mar-18	183.950	106.649
26-Apr-18	182.910	88.261
20-May-18	182.070	74.040
29-Sep-18	180.760	55.424
27-Sep-16	179.550	40.586
20-Dec-16	178.310	28.738
08-Feb-19	177.160	20.470
25-May-17	175.730	13.108
Variation in capacity		(144.172 – 13.108) = 131.064
% variation of live storage		(131.064/145.370)*100 = 90.158 %

Annexure – III

Ground Truth Scenario

Dam view

Water spread area

Vegetation in submergence

Upstream of dam

Upstream pitching

Water gauge

Jack well

Sediments in submergence

Top of dam

Main Canal

Vegetation in Submergence

Ground truth team

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