उपग्रह दूरस्थ संवेदन द्वारा शोलायार जलाशय, तमिल नाडु का अवसादन आंकलन

SEDIMENTATION ASSESSMENT OF SHOLAYAR RESERVOIR, TAMIL NADU THROUGH SATELLITE REMOTE SENSING

GOVERNMENT OF INDIA
CENTRAL WATER COMMISSION
REMOTE SENSING DIRECTORATE

भारत सरकार
केंद्रीय जल आयोग
दूरस्थ संवेदन निदेशालय

MAY 2024

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Based on CWC Office Order No T-27076/1/2018-REM SEN DTE dated 30.11.2021 the Contract Management Committee (CMC) was constituted.

Contract Management Committee (CMC) for scrutinising and approving the reports (submitted by the Consultant/Outsourced Agency/ in-house studies under any scheme) on Reservoir Sedimentation Assessment using Remote Sensing Techniques as well as using Hydrographic Survey is hereby constituted in accordance with para 8.2 of MANUAL FOR PROCUREMENT OF CONSULTANCY & OTHER SERVICES 2017 under the Chairmanship of Chief Engineer, EMO (Environmental Management Organisation), Central Water Commission with following composition and terms of reference with the approval of the Competent Authority:

S.No.	Designation
1	Chief Engineer, (EMO), CWC, Chairman
2	Director, WM, CWC, Member
3	Director, Hydrology (C), CWC, Member
4	Director, DSR, CWC, Member
5	Director (Finance), CWC, Member
6	Director, WS&RS & INCSW, CWC, Member Secretary (for Hydrographic Survey)
7	Director, Remote Sensing, CWC, Member Secretary (for Remote Sensing studies)

The terms of reference of the Contract Management Committee (CMC) will be as under:

i. Prioritisation of identified reservoirs for sedimentation studies by both the above-mentioned techniques.
ii. Preparation of draft Terms of Reference and specifications of Reservoir Sedimentation Assessment Studies using Remote Sensing techniques/ Hydrographic Survey.
iii. Preparation of Final draft RFP for Reservoir Sedimentation Assessment Studies using Remote Sensing/ Hydrographic Survey.
iv. Preparation of Final draft Notice for Inviting Proposals/bids for carrying out reservoir capacity surveys.
v. To Review the detailed program of study submitted by the consulting firm to whom work has been awarded.
vi. To Monitor and review the progress of the work and providing technical guidance for both the above-mentioned studies till completion of consultancy / studies.
vii. To examine and accord approval of the inception report, draft final report and final reports etc received from the consultants/outsourced agency from time to time.
viii. To examine and accord approval of the in-house study reports on Sedimentation assessment of reservoirs.
ix. Recommendation for release of payments, after approval of reports by Technical Advisory Committee, to consultants from time to time (as per agreement).
x. To consider the cases for extension of time, if any.
xi. To suggest changes, if any, occurring in course of time in technology; and
xii. Any other related aspects.
xiii. Committee may invite any other concerned officer as Special Invitee, if required.
xiv. The Contract Management Committee (CMC) shall meet as often as may be considered necessary.

Acknowledgement

We would like to express our deepest gratitude to our esteemed reviewers from the Central Water Commission (CWC) for their invaluable guidance and support throughout the development of the "Assessment of Sedimentation Report for the 31 Reservoirs in India using Remote Sensing Technique". Our heartfelt thanks go to Shri Rishi Srivastava, Chief Engineer (CWC), and Shri Avanti Verma, Director (CWC), for their steadfast leadership and overall guidance. Their expertise and vision have been integral to the success of this report. We are profoundly grateful to Shri Sanjay Meena, Deputy Director (CWC), and Ms. Karishma Bhatnagar Malhotra (CWC), Deputy Director, for providing essential insights and direction that have significantly enhanced the quality and clarity of our work. Additionally, we extend our sincere appreciation to Shri Devendro Moirangthem, Assistant Director, for his invaluable support. Their combined expertise, dedication, and meticulous evaluations have played a pivotal role in shaping this report, and their unwavering commitment to excellence is deeply appreciated. We also extend our sincere appreciation to the team at Geo Marine Solutions Ltd, Mangalore, for their outstanding contributions to the successful completion of this project. Our sincere thanks go to Shri Praveen Kumar, Director, for his leadership and support. We are profoundly grateful to Dr. H. S. Sudhira, our principal investigator, whose commitment and expertise have been instrumental in conducting the research and analysis for this report. Their combined expertise and commitment have been crucial in bringing this project to fruition. To all those who have contributed to this report, your dedication and hard work have been truly invaluable. Thank you for your unwavering commitment and invaluable contributions.

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Abbreviations

CWC	Central Water Commission
DSL	Dead Storage Level
FRL	Full Reservoir Level
GEE	Google Earth Engine
HS	Hydrographic Survey
IRS	Indian Remote Sensing
LISS	Linear Imaging Self Scanner
MDDL	Minimum Draw Down Level
MSL	Mean Sea Level
MWL	Maximum Water Level
NIR	Near Infra-Red
NRSC	National Remote Sensing Centre
SAR	Synthetic Aperture Radar
SNAP	Sentinel Application Platform
SRS	Satellite Remote Sensing
N.A.	Not Available
WSA	Water Spread Area

Units Used

Cumec	CUBIC METRE PER SECOND
m	METRE
M m^2	MILLION SQUARE METRE
M m^3/MCM	MILLION CUBIC METRE
Ha	HECTARE
sq. km	SQUARE KILOMETRE
mm/a	MILLIMETRE PER ANNUM

EXECUTIVE SUMMARY

Almost all reservoirs are subjected to sedimentation which reduces their storage capacity, and hence, the utilizable volume of water. Conventionally, hydrographic surveys are undertaken to assess the extent of sedimentation, however, they are expensive and time consuming. In the recent past, the availability of satellite remote sensing (SRS) has paved way for faster and cheaper methods of assessing the sedimentation in reservoirs.

The use of remote sensing data enables delineating the water spread area of reservoirs or any large water body. The water spread area of such reservoirs can be derived at or closer to the specific reservoir levels. Gathering the remote sensing data corresponding to the specific levels of the reservoir enables us to ascertain the corresponding water spread area. With these data and using the trapezoidal formula, the cumulative capacity of the reservoir can be estimated.

In the present assessment, microwave satellite remote sensing data from Sentinel 1A are used for studying the sedimentation of Sholayar reservoir in Tamil Nadu. Accordingly, the data are analysed using Google Earth Engine. The water pixels derived are then processed using QGIS to derive the area, and contours at the respective levels are prepared.

Sholayar River is one of the main tributaries of the Chalakudi river. It has its source in Valparai Estate and runs in a westerly direction for about 30 miles before it joins the Parambikulam River. The total catchment area of this river up to its inflow into the Parambikulam River is 100 square miles, of which 55 square miles are in Tamil Nadu State and the rest in Kerala. The reservoir is located on the river Sholayar at 10° 18′ 00" N and 76° 53′ 00" E. The project was first impounded in 1972. The catchment area of the project is 121.68 sq. km. The original gross and live storage capacity of the reservoir are 152.48 MCM and 142.88 MCM respectively.

Based on the analysis, the live storage capacity of Sholayar reservoir has been found to be 129.49 MCM in 2020-21 against the live storage capacity of 142.88 MCM as per the dam authorities (1972). This suggests a loss in live capacity by 13.39 MCM, which is about 9.37% of the live capacity. Thus, the annual rate of live capacity loss is 0.19%. In 2007, the CWC had undertaken a satellite remote sensing survey that reported the capacity as 134.16 MCM. The annual rate of live capacity loss considering the 2007 assessment was 0.17%. Considering this, it does not suggest a significant annual rate of live capacity loss.

1.INTRODUCTION

India – the largest country in the world in terms of population – has about 17.75% of the world's population, about 4% of the world's water resources, and 2.44% of the total geographical land area of the world. Therefore, in spite of having an average annual 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 situation of water resources availability gets murkier due to topographical and other constraints. Due to this, the total utilisable water resources in the country are about 1126 BCM (690 BCM of surface water and 436 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, that is, in 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 a resource that is 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, many 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 such as boat echo sounder are being replaced by hydrographic data acquisition systems (HYDAC) and HITECH method using Differential Global Positioning System (DGPS). The conventional techniques are either time consuming or costly and require considerable manpower. Remote sensing technique to calculate the present live capacity of reservoirs is found to be very useful in this context owing to its synoptic and repetitive coverage. The surveys based on remote sensing data are faster, economical, and more reliable. These surveys can 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 Sholayar reservoir in Tamil Nadu undertaken by the Central Water Commission, New Delhi in collaboration with Geo Marine Solutions Private Limited, Mangaluru, Karnataka.

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. 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 erosion in the area. Sediment transportation depends upon the slope of the catchment, channel geometry and nature of riverbank and bed. Deposition is a function of the bed slope of the reservoir, length of the 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,

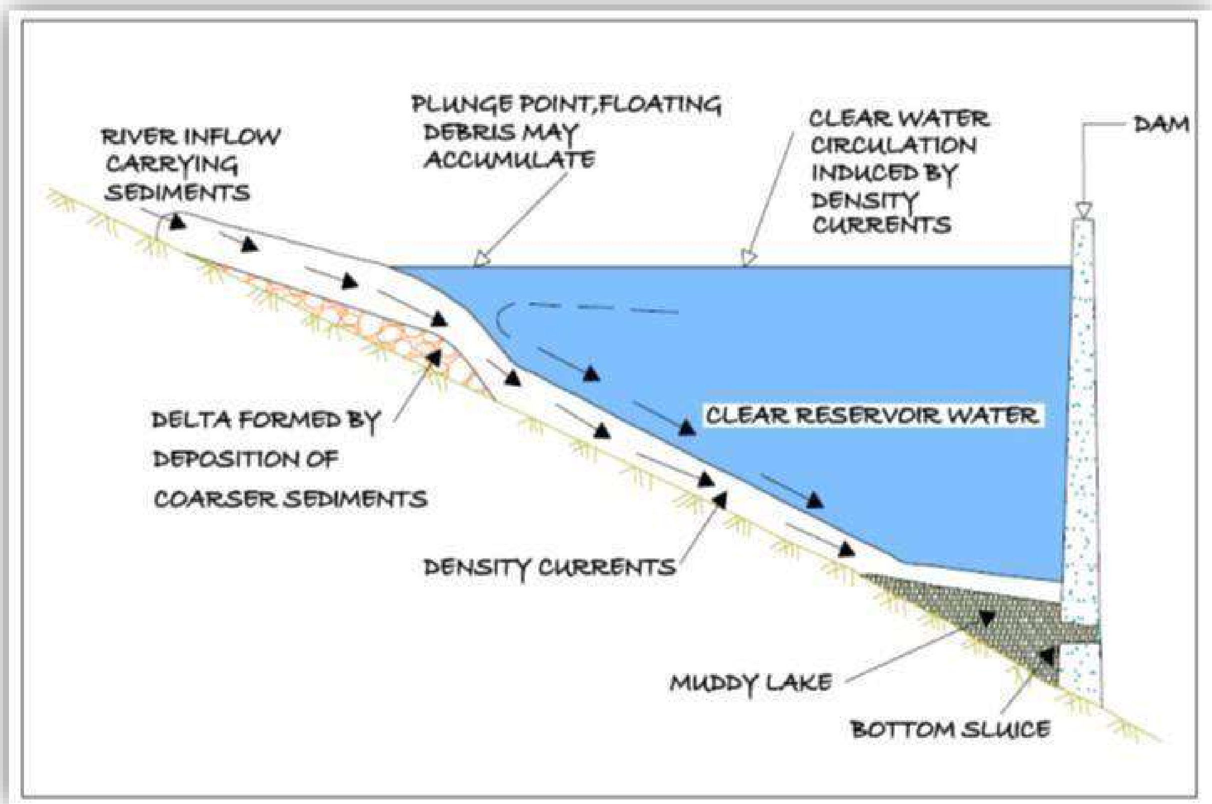


Figure 1: Conceptual sketch of density currents in a reservoir.

its velocity decreases rapidly 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 in the dead as well as live storage capacities.

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. However, it is now understood that deposition takes place throughout the reservoir reducing the incremental capacity at all elevations.

Longitudinal deposition patterns in the reservoir 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 Figure 2 below.

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 of the sediment to be carried into the vicinity of the dam. Tapering deposits occur when deposits become progressively thinner moving towards the dam. This is a common pattern in long reservoirs normally held at high pool level and reflects the progressive deposition of fine sediment 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 such as amount of sediment load, size distribution, fluctuations in stream discharge, shape of reservoir, stream valley slope, vegetation at

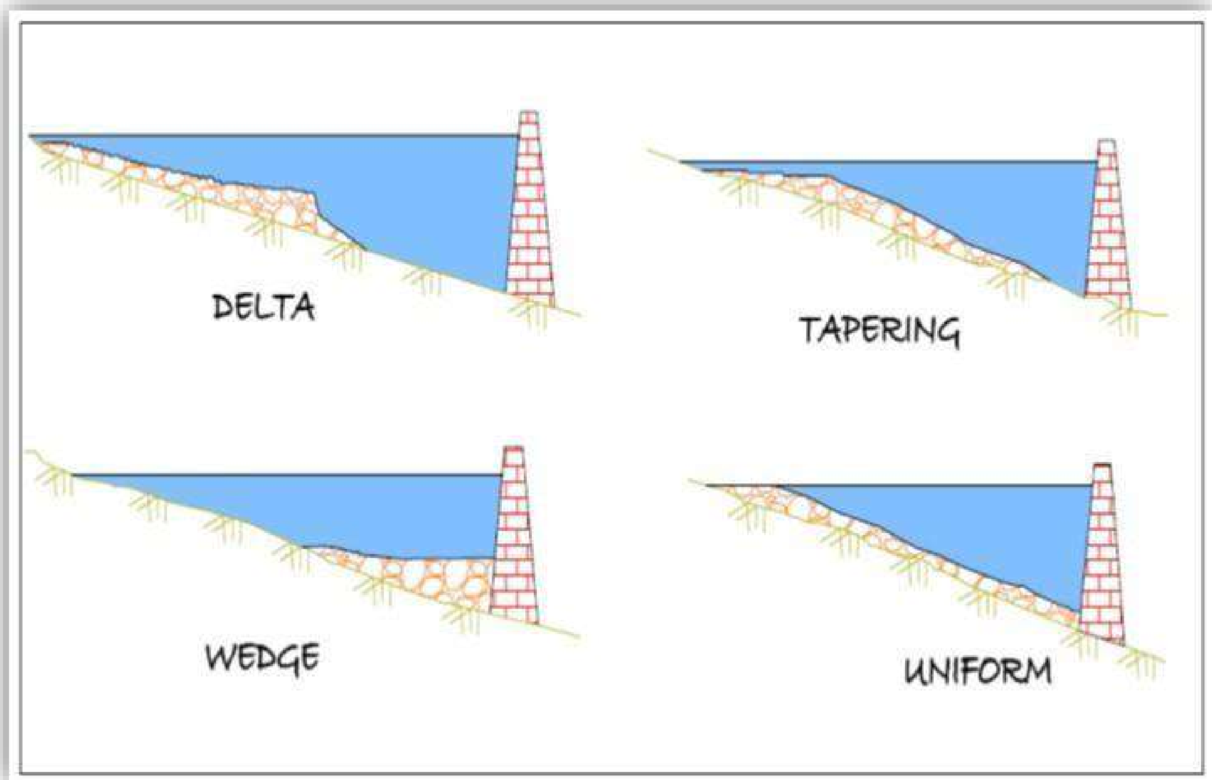


Figure 2: Longitudinal Patterns of sediment deposition in reservoirs.

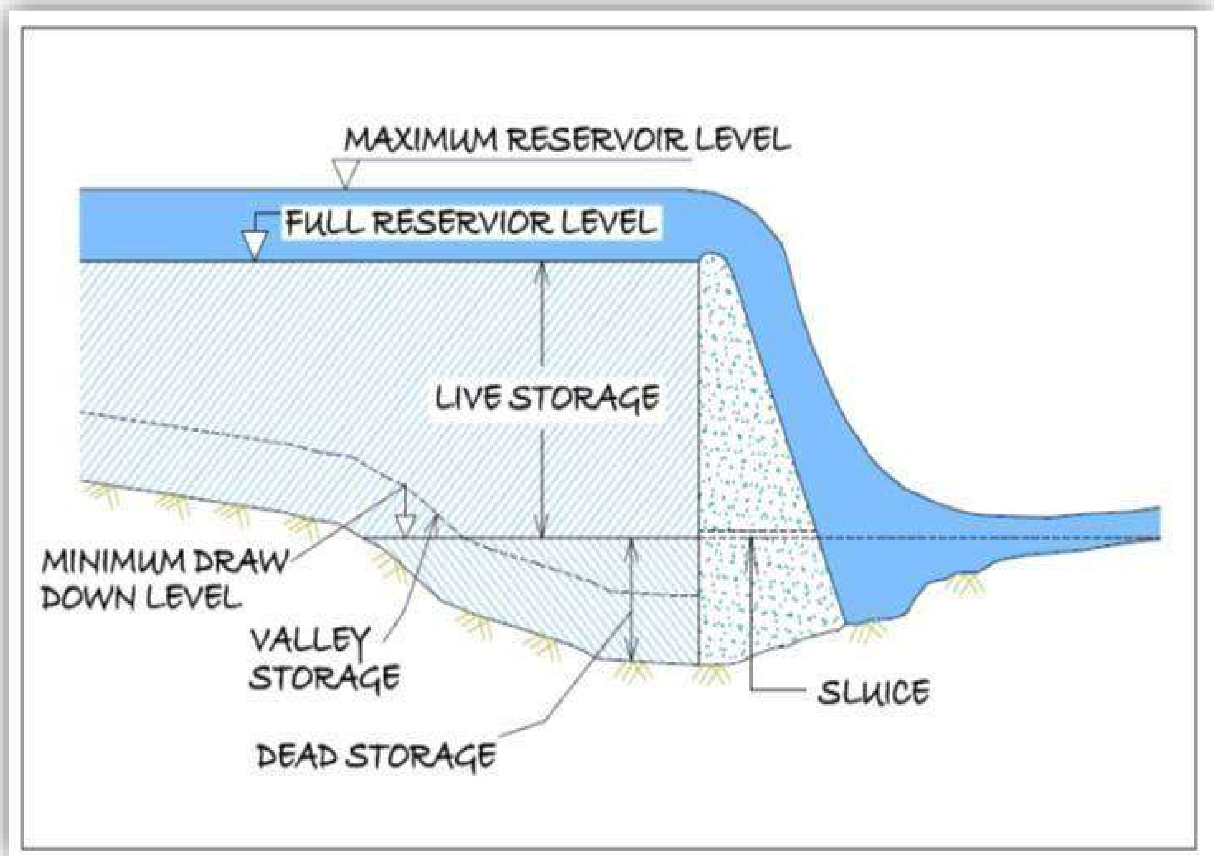


Figure 3: Conceptual sketch of different levels in a reservoir.

the head of the reservoir, location and size of reservoir, and outlets control the location of sediment deposits in the reservoir.

Figure 3 shows the different levels in the reservoir wherein the capacity is affected. Reservoirs operate between Minimum Draw Down Level (MDDL) and Full Reservoir Level (FRL). The storage between these two levels is the live storage. The storage below MDDL is the dead storage. Water stored along the valley bed is known as valley storage.

3. CONTROL OF SEDIMENTATION

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

1. Soil and water conservation measures within the drainage basin which include 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. Measures are required to ensure that the storage capacities available are not lost or depleted by accelerated sedimentation.

4. REMOTE SENSING IN RESERVOIR SEDIMENTATION

Remote sensing is the art and science of collecting information about earth's features 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, while the emitted radiation depends upon temperature and emissivity. The radiations are recorded by the sensor on-board the satellite and then are transmitted back to earth. Difference between features depends upon the fact that responses from different features like vegetation, soil, and water are different and discernible. Data received at ground stations, is digitally or visually interpreted to generate thematic maps.

The data from satellites such as Landsat, SPOT and IRS are useful for mapping and monitoring the surface water bodies and other land resources based on which, better water management strategies could be planned. Data from microwave remote sensing technique such as SENTINEL-1 is more useful because it is an imaging radar mission providing continuous all-weather, day-and-night imagery at C-band. The SENTINEL-1 constellation provides high reliability, improved revisit time, higher geographical coverage, and rapid data dissemination to support operational applications in the priority areas of marine monitoring, land monitoring, and emergency services.

Spectral response of water is affected by variables like time of the year, sun elevation angle, water vapour content in the atmosphere, roughness of water surface, water colour, turbidity, type and concentration of suspended particles, depth of water, characteristics of bottom material, and submerged or emergent vegetation.

Reservoir sedimentation surveys are essentially based on mapping of water-spread area at the time of satellite over pass. Multi-date satellite data, covering the operating level of reservoir at close interval, is needed. Water spread area is the water level contour at that level. Using different contours, capacity between them is calculated. With sedimentation, the water spread area of the reservoir reduces at different levels. The water spread area and the elevation information is 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 the change in capacity between different levels.

Remote sensing-based reservoir capacity estimation has certain limitations. The capacity estimation works between MDDL and FRL only because these are the levels between which reservoir operates. Thus, changes can be estimated only in live capacity of reservoirs. For capacity estimation below MDDL corresponding to dead storage, other methods like hydrographic survey need to be used. Availability of cloud free data throughout reservoir operations, which was a limitation in earlier optical analysis, has now been taken care of by using microwave datasets that are not affected by weather or illumination conditions. This technique gives accurate estimates for fan shaped reservoirs where there is a considerable change in water spread area with change in water level.

5. OBJECTIVES

The objective of the study is to estimate live capacity loss of each reservoir due to sedimentation using satellite remote sensing. The following objectives are achieved in the study.

- Updating Elevation – Area – Capacity curve based on satellite remote sensing analysis of live storage.
- Estimation of storage loss due to sedimentation.

6. APPROACH FOR THE PRESENT STUDY

Remote sensing technique makes use of water-spread of the reservoir between maximum and minimum operating level during the observation period. Because the reservoir levels do not generally go below the MDDL, water spread observations are not possible below MDDL. The same are to be extrapolated from observed elevation area curve to find out capacity below MDDL.

6.1 CRITERIA FOR SELECTION OF DATES FOR ANALYSIS

The selection of the satellite data for the present study is based on the following guidelines given in the Memorandum of Understanding signed between CWC, New Delhi and Geo Marine Solutions Pvt Ltd.:

- 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.
- To carry out sedimentation analysis through SRS technique to cover the entire live storage zone of the reservoir.
- 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 a minimum of 80 % of live storage capacity is covered by the available cloud free dates of satellite pass on maximum and minimum reservoir levels.

7. DATA SOURCES

7.1. SATELLITE DATA

Based on the feasibility studies, Sentinel 1 data were gathered and used in the analysis.

7.2. FIELD DATA

The reservoir water level data of the corresponding satellite images was acquired from India Water Resources Information System (India-WRIS). The following data has been obtained from project authorities:

- Elevation – Area – Capacity data
- Salient features of the reservoirs, levels and capacity data on specified dates.

8. METHODS / DATA ANALYSIS

The reservoirs are generally full during the monsoon. Depending on the extent of rainfall and inflows to the reservoir, the reservoir levels are at FRL or near FRL during these months. However, based on the utility of water and discharge of water by dam authorities according to the needs, water level recedes, and generally reaches near MDDL pre-monsoon (during the months of April-May-June). Since the water year is designated from June to May of the following year, to ascertain the sedimentation in reservoirs, data is analysed corresponding to the water years. Typically, data from one or two water years are gathered in such studies.

The use of remote sensing data enables delineating the water spread area of reservoirs or any large water body. The water spread area of such reservoirs can be derived at or closer to the specific reservoir levels. Gathering the remote sensing data corresponding to the specific levels of the reservoir enables us to ascertain the corresponding water spread area. With these data and use of the trapezoidal formula, the cumulative capacity of the reservoir can be estimated. The overall methodology adapted is shown as a flow chart in Figure 4.

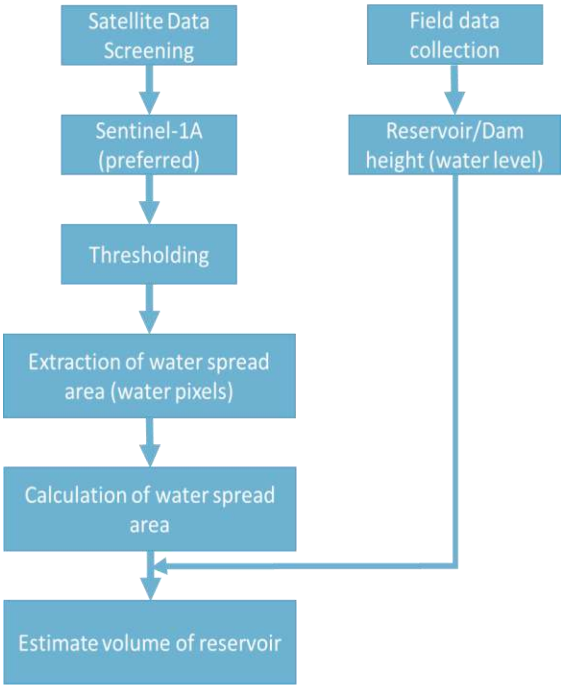


Figure 4: Flowchart of steps followed for data analysis.

8.1 CLOUD-BASED GOOGLE EARTH ENGINE FOR GEOSPATIAL ANALYSIS

With the challenges accompanying the use of desktop systems for geospatial analysis (computation), the emergence of cloud-based Google Earth Engine (GEE) has been a welcome relief, particularly for data storage and computation. GEE is essentially a computing platform that allows users to perform geospatial analysis using Google's cloud infrastructure. GEE comes with a Code Editor which is a web-based interface for writing and running scripts. Moreover, GEE has an Explorer, which is a lightweight geospatial data viewer. These features are integrated with Google's cloud to access a large set of global and regional data accessible through the Earth Engine Data Catalog.

Earth Engine stores more than thirty years of historical imagery and scientific datasets, which get updated and expanded daily. It also has a range of spatial manipulation tools which allow to detect changes, map trends, and quantify differences on the Earth's surface. This ability to analyse and manipulate data according to the user's needs, differentiates this application from the traditional Google Earth.

Earth Engine is integrated with Python and Java script through its API. APIs for JavaScript and Python can be hosted on Github. The Earth Engine (EE) Code Editor is accessible online at https://code.earthengine.google.com, the web-based integrated development environment (IDE) for the Earth Engine using JavaScript. Code Editor features are designed for fast and easy development of complex geospatial workflows. The Code Editor has various elements making complex analysis and visualisation fast and easy.

8.1.1 ADVANTAGES OF USING GEE

Though GIS and remote sensing plays a critical role in the management of water resources, many practitioners in this field are constrained by the availability of tools and computing resources to use these techniques effectively. Most of the applications/software are expensive and the satellite data file sizes are huge which makes it difficult for any stand-alone device to bear the data load without any server.

As noted earlier, advances in cloud computing technology have given rise to platforms such as GEE JavaScript open-source cloud platform, which provide access to a large pool of computational resources and datasets. With the help of this large repository of publicly available geospatial data on GEE catalog, one can very easily and effectively carry out most of the geospatial analysis.

GEE has extensive tutorial platform to assist with JavaScript and Python. It also supports API for working with external applications. The tutorial is exhaustive and has specific examples related to water resources such as Surface Water Mapping, Precipitation Time Series Analysis, Land Use Land Cover Classification, Flood Mapping and Drought Monitoring, among others.

GEE is being widely used in water resource studies such as monitoring the storage volume of water reservoirs (Condeça et al., 2021), detection of river channel change (Boothroyd et al., 2020), monitoring of surface sediments (Markert et al., 2018) and water quality monitoring (Hansen et al., 2015). Most of these studies highlight the use of GEE and its benefits such as extensive collection of imagery data, efficient computational methods to speed image processing and model development or application tasks, API and developer environment for model prototyping, no cost to obtain, store, or process data, and ease of sharing datasets through JSON and workspaces.

8.2 SEDIMENTATION STUDIES USING GOOGLE EARTH ENGINE

The traditional methods for assessing sedimentation in the reservoir using satellite remote sensing are time-consuming and resource intensive. On the contrary, initial explorations for employing GEE for accessing Sentinel 1A SAR data, working with it to derive the water spread area, and perform the analysis seem to be much more efficient and timelier.

The steps involved in carrying out the sedimentation assessment using GEE are outlined below:

1. Browse the Sentinel 1A SAR data through Data Catalog and note the required parameters.
2. On GEE Code Editor, indicate the following parameters to fetch the data:
   - Satellite Platform: S1A_*
   - Product Type: GRD
   - Polarisation: VV (& VH)
   - Sensor Mode: IW
3. Filter the Sentinel-1 SAR collection according to data collection types.
4. Filter speckle noise by selecting the VV polarisation band.
5. Smoothen the image by applying a focal median of 30 m or 100 m.
6. Add speckle filtered image to map with raw SAR image for the extracted image and check the histogram.
   - Typically, if the processed data is around a reservoir (water spread area), one can notice two peaks– one of them is for water and the other is for non-water (land).
   - Based on the histogram - thresholding approach, check for the values around -14, to see if it is on the trough of the peak and is not overlapping with the other histogram. Depending on the landscape, this trough can be anywhere between -10 to -18. Decide the threshold based on this histogram.
7. Reclass the image for less than the threshold (e.g., -14, or the appropriate threshold, decided based on the histogram in the previous step) to 1 and the rest to 0.
8. Now the reclassified image can be converted to polygon. Once the polygon is cleaned for any rings and correct geometries, check the area of the polygon.
9. Smoothen the polygon so that the contours for that level can be derived appropriately.
   a. Convert the polygon to polyline.
   b. Smoothen the polyline with a tolerance of 8-10 metres.
   c. Convert the polyline back to polygon and derive the area.
10. Check for the area again and update the table with the surface area of the water spread.
11. Estimate the volume using the trapezoidal formula for each level.
12. Calculate the sedimentation and rate based on the above and compare them with previous studies.

The above steps are repeated for all levels of the reservoir.

8.3 ESTIMATION OF WATER SPREAD AREA (USING SAR MICROWAVE DATA THRESHOLDING APPROACH)

Using SAR data, the water spread area and the capacity of the reservoir are assessed using the trapezoidal formula after obtaining the water level of the reservoir. The Sentinel-1 SAR data has proven to be the most promising data for such studies. The speckling effect of SAR data, which gives a granularity/haziness at the borders, can be filtered out by applying the proper threshold for any dataset.

To start with, the dates on which the satellite data is available for Sentinel 1 over the reservoir of interest is gathered. The corresponding water level data can be gathered from India-WRIS and for those dates, for which the analysis can be undertaken. The first step in analysing SAR data for deriving water spread area is to plot the histogram of the VV polarisation. The histogram is used to determine the threshold. Typically, there are two peaks, one for water and the other for non-water (land). The x-axis represents the value in decibels and the Y axis represents the frequency.

From the histogram of VV polarisation of a reservoir data set, the smaller peak on the left side is for water spread area and the larger peak (on the right) is for land area. Following the standard method for speckle correction, a median filter is applied for the VV polarization band with a radius of 10 metres that removes the speckle noise. Based on the histogram, a threshold was set for segmenting the water pixels. The thresholds were set separately for each image as per their histograms for the analysis. Thus, those pixels under the threshold are reclassified as water and the rest as non-water pixels.

After deriving the water pixels, they are exported separately as a raster. The raster is then converted into a polygon and then smoothening of the lines (polylines) are done to derive the respective contours using QGIS. Then, the area of the water spread polygon is calculated.

8.4 ESTIMATION OF LIVE STORAGE CAPACITY OF THE RESERVOIR

The assessment of live storage capacity of reservoir involves deriving the water spread area from the SAR data and comparing with the observed level of reservoir corresponding to the satellite pass dates. The basic principle of assessing the sedimentation using remote sensing approach is that the water spread at any elevation reduces due to the sediment deposition with time (Goel et al., 2002).

Considering the volume stored between two dates or elevation as trapezoid (as shown in Figure 5), the capacity between these two elevations can be calculated using the trapezoidal formula.

$$V = \frac{h}{3} * [A_1 + A_2 + \sqrt{(A_1 * A_2)}]$$

where,

'V' is the reservoir capacity between two successive elevations h_1 and h_2,

'h' is the elevation difference (h_1-h_2),

'A_1 & A_2' are areas of reservoir water spread at elevations h_1 & h_2.

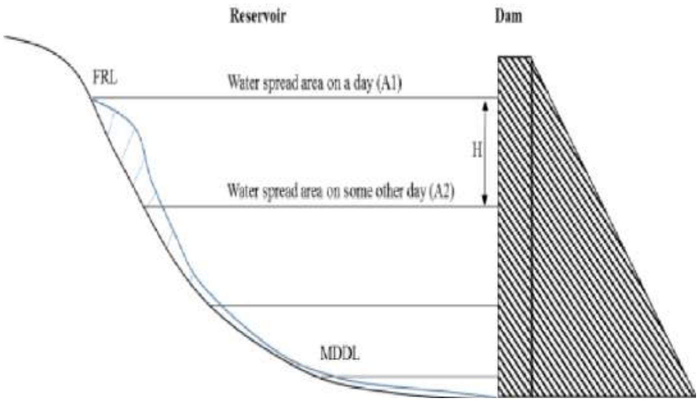


Figure 5: Sedimentation profile in a reservoir (Prasad et al., 2018).

9.SHOLAYAR RESERVOIR

Sholayar River is one of the main tributaries of the Chalakudi river. It has its source in Valparai Estate and runs in a westerly direction for about 30 miles before it joins the Parambikulam River. The total catchment area of this river up to its inflow into the Parambikulam River is 100 square miles, of which 55 square miles are in Tamil Nadu State and the rest in Kerala. The Sholayar Dam, with a maximum height of 345 feet, is constructed across the Sholayar River as one of the components of the prestigious Parambikulam Aliyar Project and has a capacity of 5392 million cubic feet.

The reservoir is located on the river Sholayar at 10° 18′ 00” N and 76° 53′ 00” E. The project was completed in 1972. The catchment area of the project is 121.68 sq. km. The original gross and live storage capacity of the reservoir are 152.48 MCM and 142.88 MCM respectively. The index map of the reservoir is shown in Figure 6. In the case of Sholayar reservoir, the height

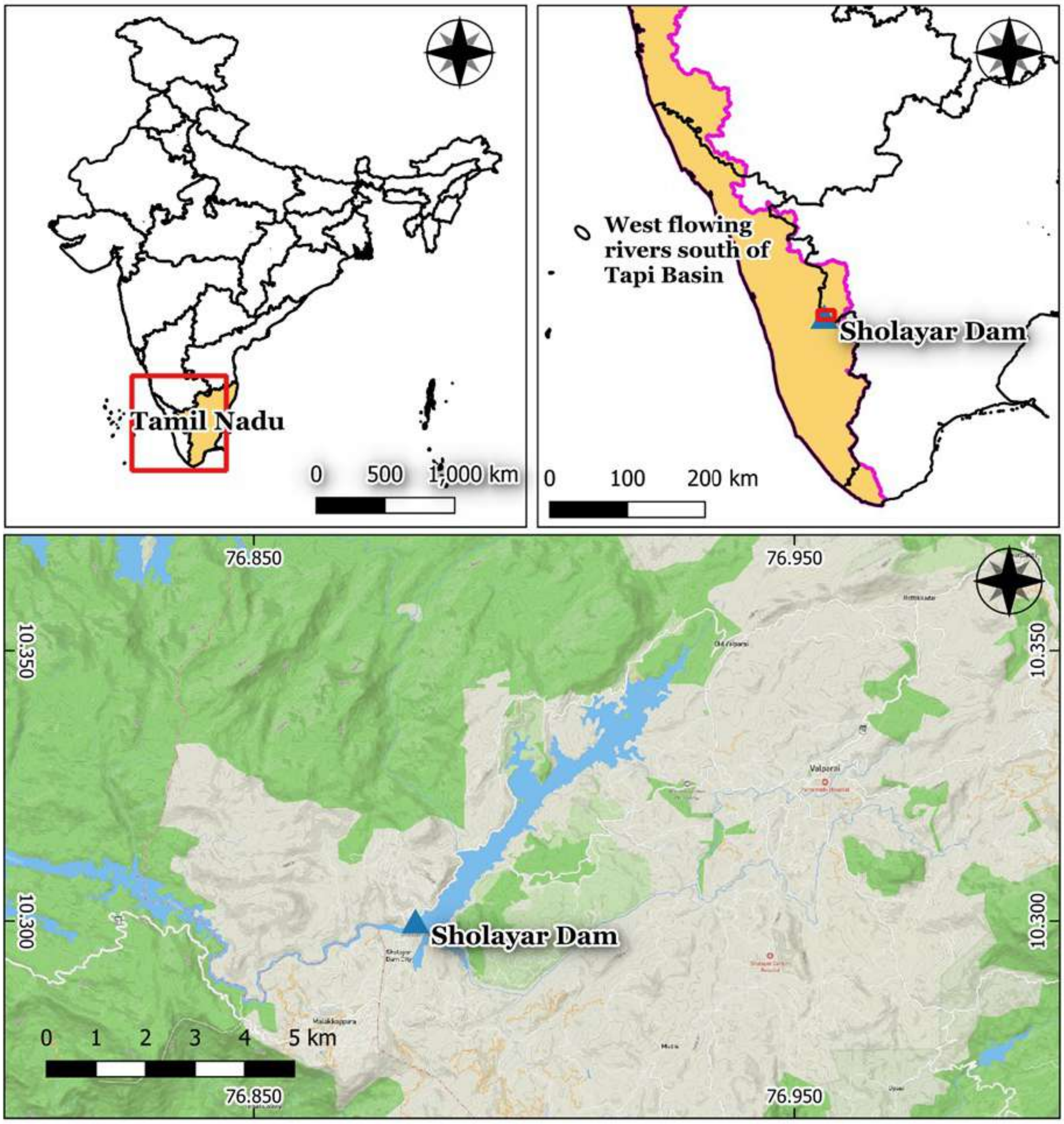


Figure 6: Index map of Sholayar Reservoir.

difference between FRL (1002.79 m) and MDDL (954.02 m) is 48.77 m.

9.1 SATELLITE DATA

Sentinel 1 data for the following dates has been used in the analysis. Table 1 depicts the details of the date of satellite pass and the corresponding level in the reservoir on those dates.

Table 1: Date of pass for satellite data for Sholayar Reservoir.

Date of Pass (DOP)	Reservoir Levels (m)	Satellite Sensor
07-04-2021	954.57	Sentinel 1A
20-05-2022	963.78	Sentinel 1A
25-01-2021	971.42	Sentinel 1A
13-01-2021	975.64	Sentinel 1A
01-01-2021	979.80	Sentinel 1A
17-07-2020	985.32	Sentinel 1A
29-07-2020	987.14	Sentinel 1A
08-12-2020	990.93	Sentinel 1A
26-11-2020	998.17	Sentinel 1A
22-09-2021	1002.92	Sentinel 1A

The first step in analysing SAR data for deriving water spread area is to plot the histogram of the VV polarisation (Figure 7). The histogram is used to determine the threshold. As discussed earlier, based on the histogram, a threshold was set for segmenting the water pixels. The thresholds were set separately for each image as per their histograms for the analysis. Thus, those pixels under the threshold are reclassified as water and the rest as non-water pixels.

After deriving the water pixels, they are exported separately as a raster. The raster is then converted into a polygon and then smoothening of the lines (polylines) are done to derive the respective contours using QGIS. Then, the area of the water spread polygon is calculated (Table 2).

Table 2: Water Spread Areas estimated from Satellite Images for Sholayar Reservoir.

Date of Pass (DOP)	Reservoir Levels (m)	Area (sq. km)
07-04-2021	954.57	0.86
20-05-2022	963.78	1.55
25-01-2021	971.42	2.19
13-01-2021	975.64	2.28
01-01-2021	979.80	2.55
17-07-2020	985.32	2.99
29-07-2020	987.14	3.26
08-12-2020	990.93	3.83
26-11-2020	998.17	4.39
22-09-2021	1002.92	4.78

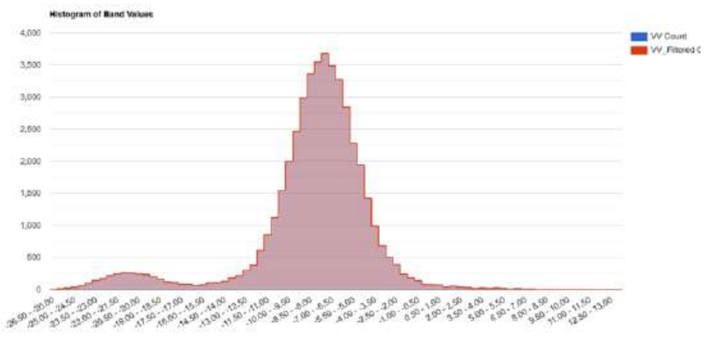
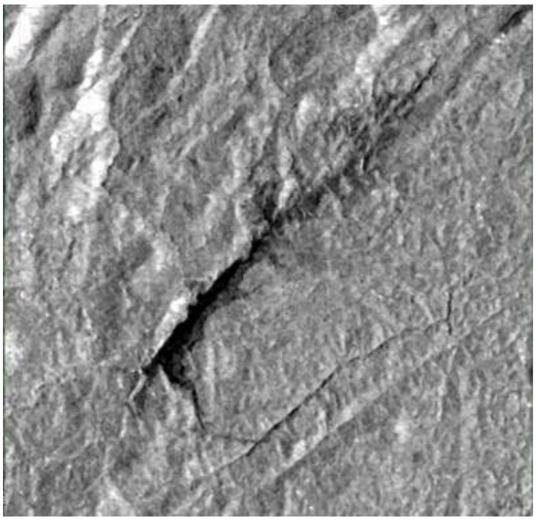


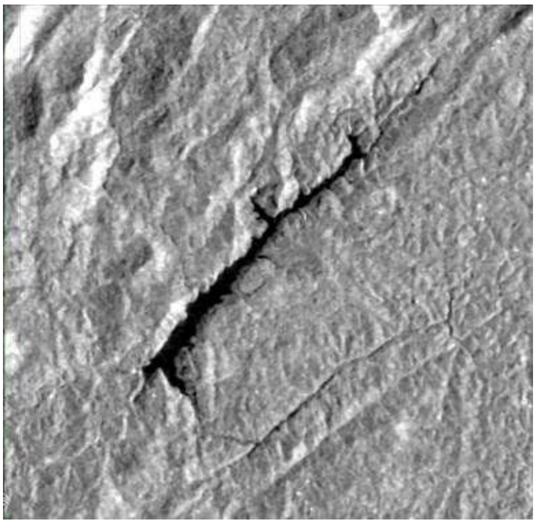
Figure 7: Histogram of VV for Sholayar Reservoir.

9.2 RESERVOIR CAPACITY ESTIMATION

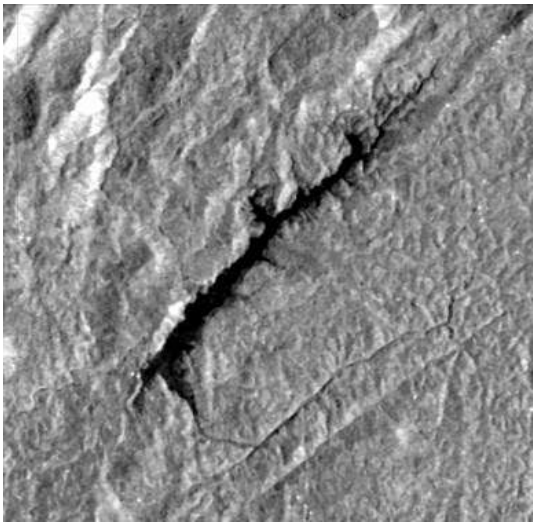
The water spread pixels derived for all the levels are presented in Figure 8. As seen, the extent of the water spread area while the reservoir levels are near MDDL is lesser, and when the reservoir levels are near FRL, the water spread area is larger. The water spread at different levels derived are presented in Figure 9.



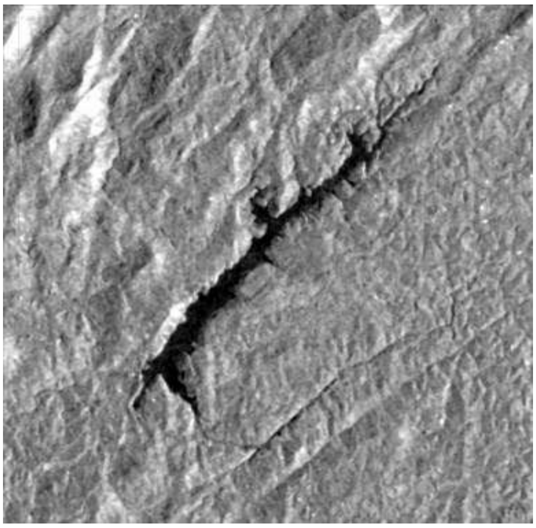
Date: 07-04-2021 | Reservoir level: 954.570 m



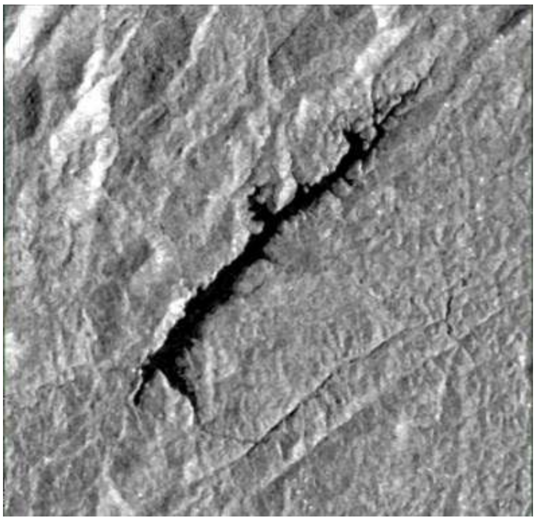
Date: 20-05-2022 | Reservoir level: 963.778 m



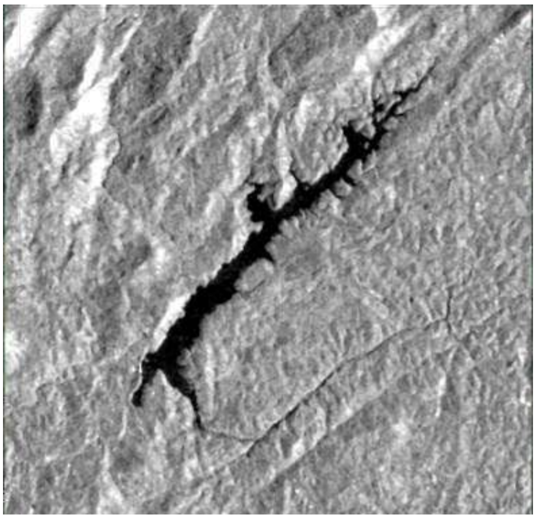
Date: 25-01-2021 | Reservoir level: 971.422 m



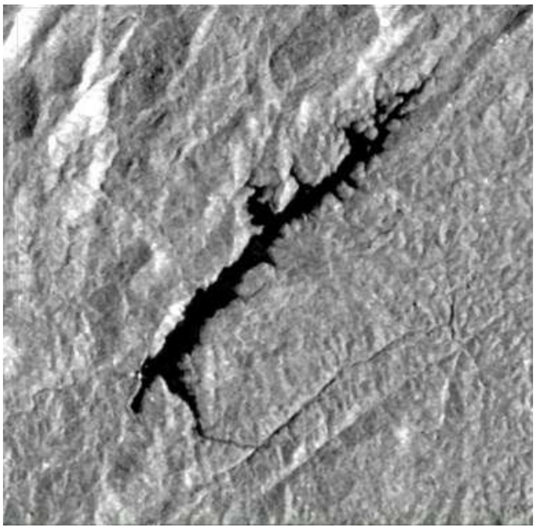
Date: 13-01-2021 | Reservoir level: 975.637 m



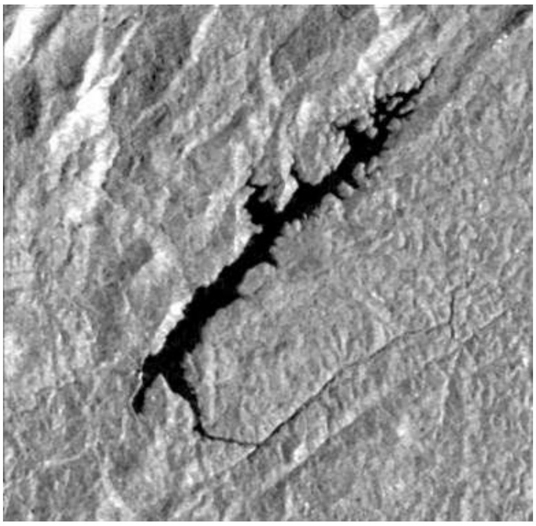
Date: 01-01-2021 | Reservoir level: 979.798 m



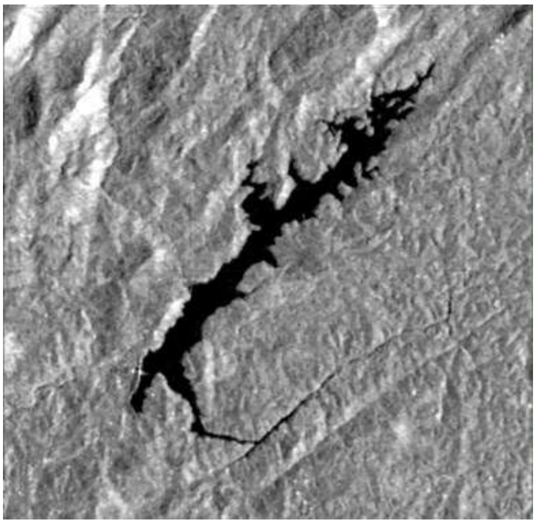
Date: 17-07-2020 | Reservoir level: 985.321 m



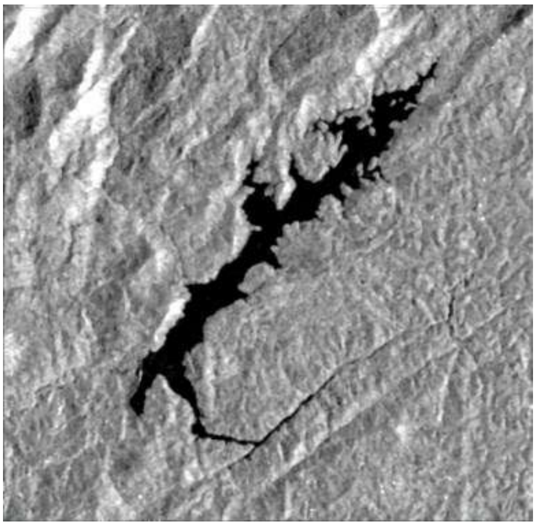
Date: 29-07-2020 | Reservoir level: 987.137 m



Date: 08-12-2020 | Reservoir level: 990.926 m



Date: 26-11-2020 | Reservoir level: 998.171 m



Date: 22-09-2021 | Reservoir level: 1002.917 m

Figure 8: Sentinel-1A images for Sholayar Reservoir.

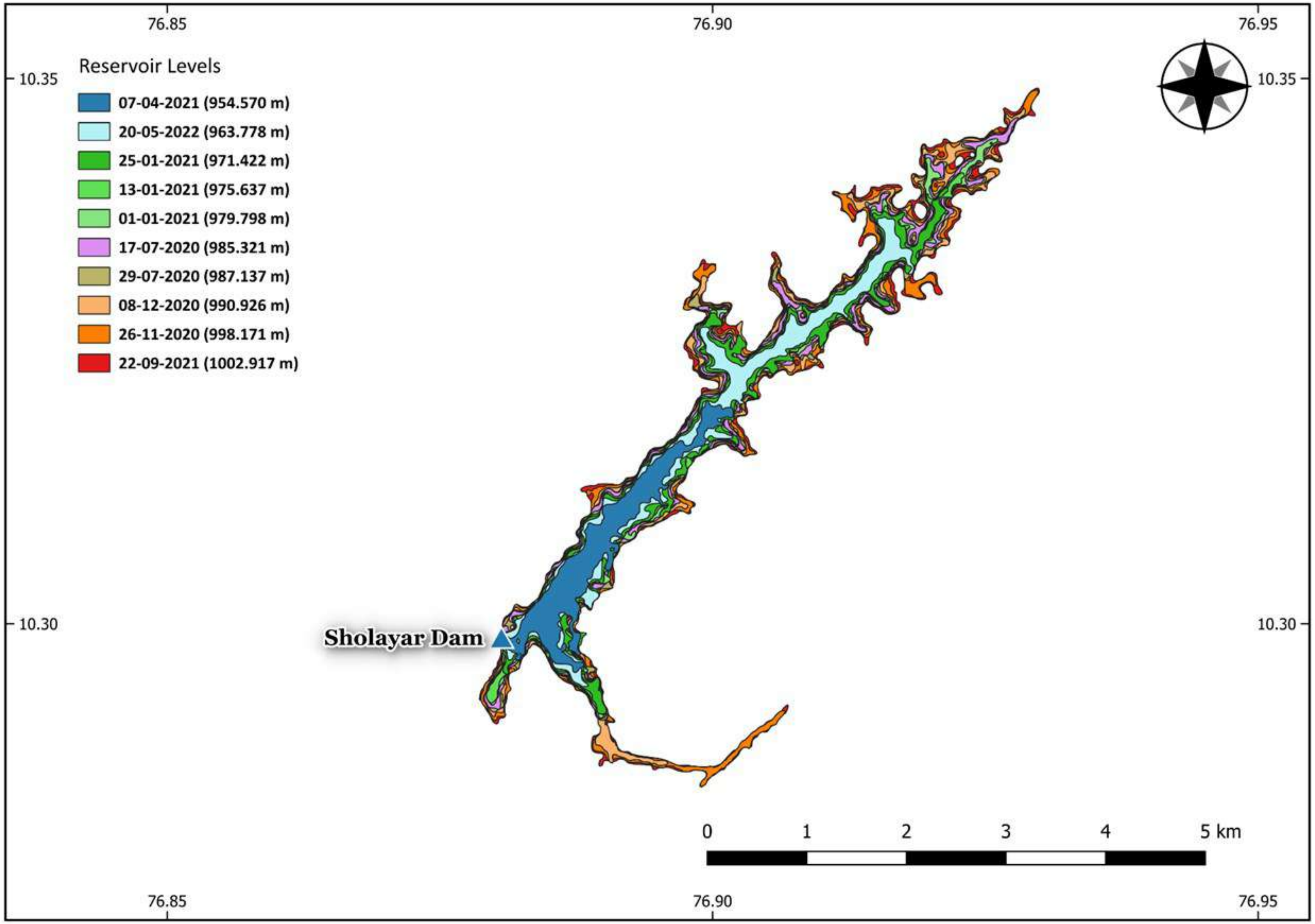


Figure 9: Water spread area at different levels of Sholayar Reservoir.

Area elevation curve is plotted using these water-spread areas for different water level in the reservoir and a best-fit polynomial equation of second order is derived as given below.

$$y = 0.00049x^2 - 0.88191x + 394.57565$$

$$(R^2 = 0.99138)$$

where, x is elevation in meters; y is the water spread area in sq. km.

Table 3 gives the values of live storage capacity and the submergence areas at a regular interval of 5.0 m are obtained using the abovementioned best-fit polynomial equation at different elevations. The modified live capacity - elevation curve and modified elevation – area –capacity curves are plotted and shown in Figure 11 and Figure 12, respectively.

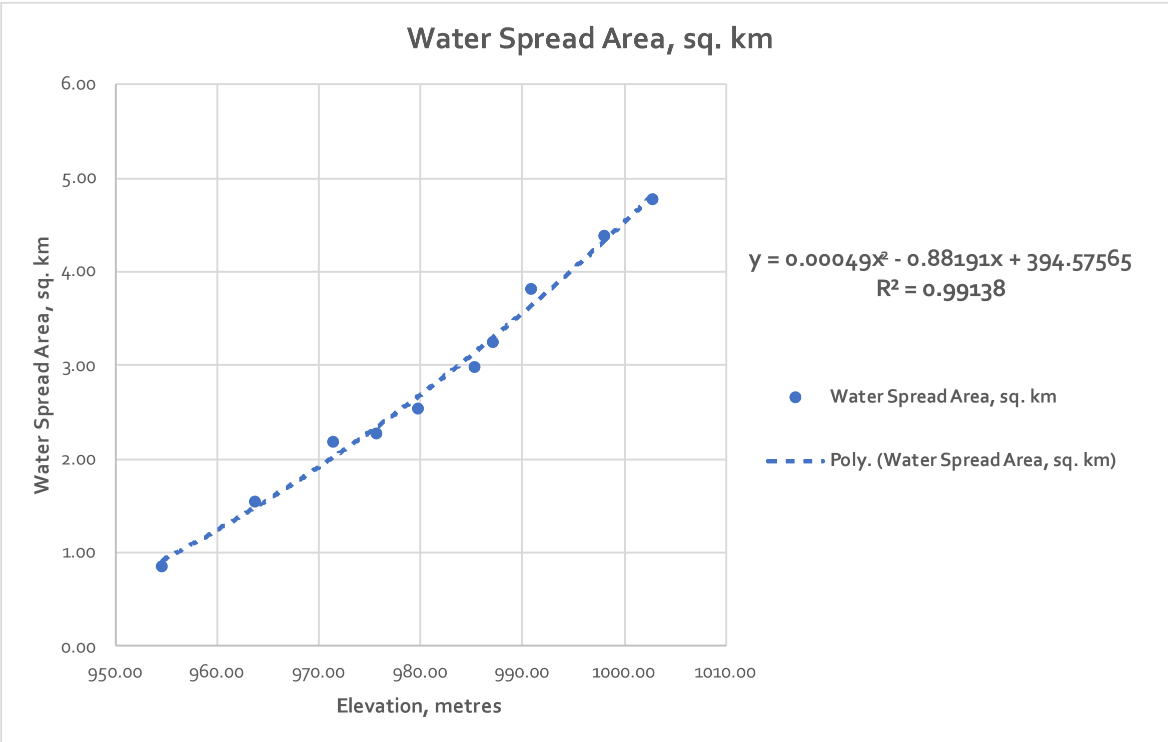


Figure 10: Observed Elevation vs. Observed Water Spread Area and Best Fit Curve for Sholayar Reservoir.

The elevation - area curve using this equation is and shown in Figure 10. Water spread areas derived from satellite data for various dates are also marked on the curve.

Considering the volume between two elevations or satellite pass as trapezoid, the volume of the reservoir is calculated using the trapezoidal formula as described above. The capacity obtained between each elevation is used to calculate the cumulative live storage capacity of the reservoir.

9.3 COMPARISON WITH EARLIER STUDIES/SURVEYS

A comparison of the live storage capacity of the present satellite remote sensing survey with the capacity table shared by the dam authorities for various elevations respectively is given below in Table 4.

The chart showing the comparison of live capacity of SRS survey with the original and the previous assessment's capacity table is shown in Figure 13.

Table 3: Aerial extent of Sholayar reservoir at regular interval (5.0 m) using SRS Survey 2020-21.

Reservoir Levels (m)	Water spread area by trend line (sq. km)	Segmental Live Capacity (MCM) by SRS technique	Cumulative Live Capacity (MCM) by SRS technique
MDDL 954.02	0.886	0.000	0.000
955.00	0.942	0.896	0.896
960.00	1.242	5.443	6.339
965.00	1.567	7.007	13.346
970.00	1.916	8.692	22.038
975.00	2.290	10.500	32.538
980.00	2.688	12.431	44.970
985.00	3.111	14.485	59.455
990.00	3.559	16.662	76.116
995.00	4.031	18.961	95.078
1000.00	4.528	21.384	116.462
FRL 1002.79	4.815	13.031	129.493

Table 4: Comparison of Live Storage Capacity (MCM) for Sholayar Reservoir.

Reservoir Levels (m)	Original Survey (MCM), 1972	SRS by CWC (MCM), 2007	SRS by CWC, (MCM), 2020-21
954.02	0.00	0.00	0.00
955.00	0.97	0.68	0.90
960.00	6.79	5.60	6.34
965.00	14.29	12.85	13.35
970.00	23.78	22.35	22.04
975.00	35.52	34.01	32.54
980.00	49.62	47.74	44.97
985.00	66.22	63.46	59.45
990.00	84.56	81.07	76.12
995.00	105.17	100.5	95.08
1000.00	128.65	121.64	116.46
1002.79	142.88	134.16	129.49

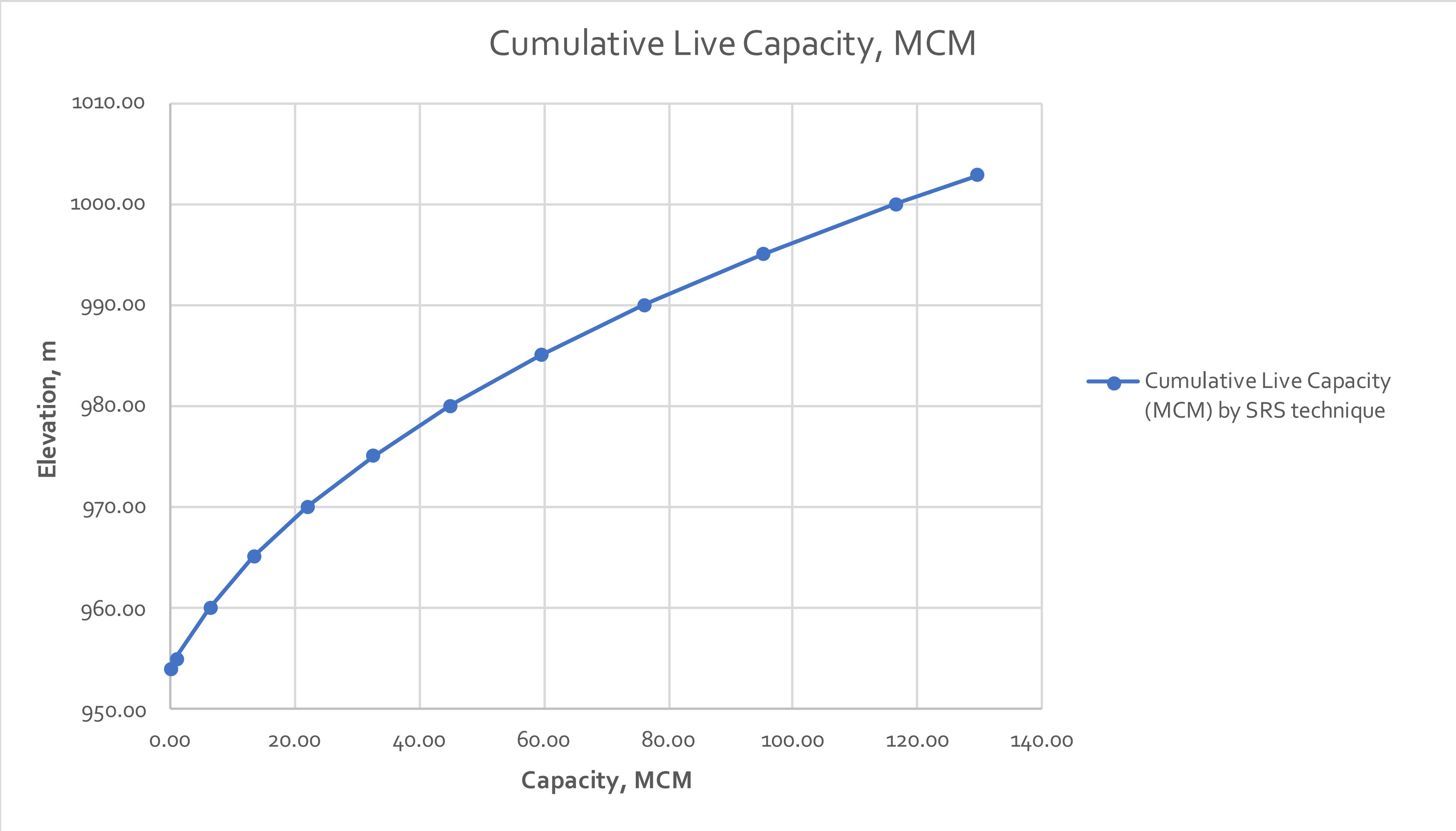


Figure 11: Modified live capacity - elevation curve (SRS technique) for Sholayar Reservoir.

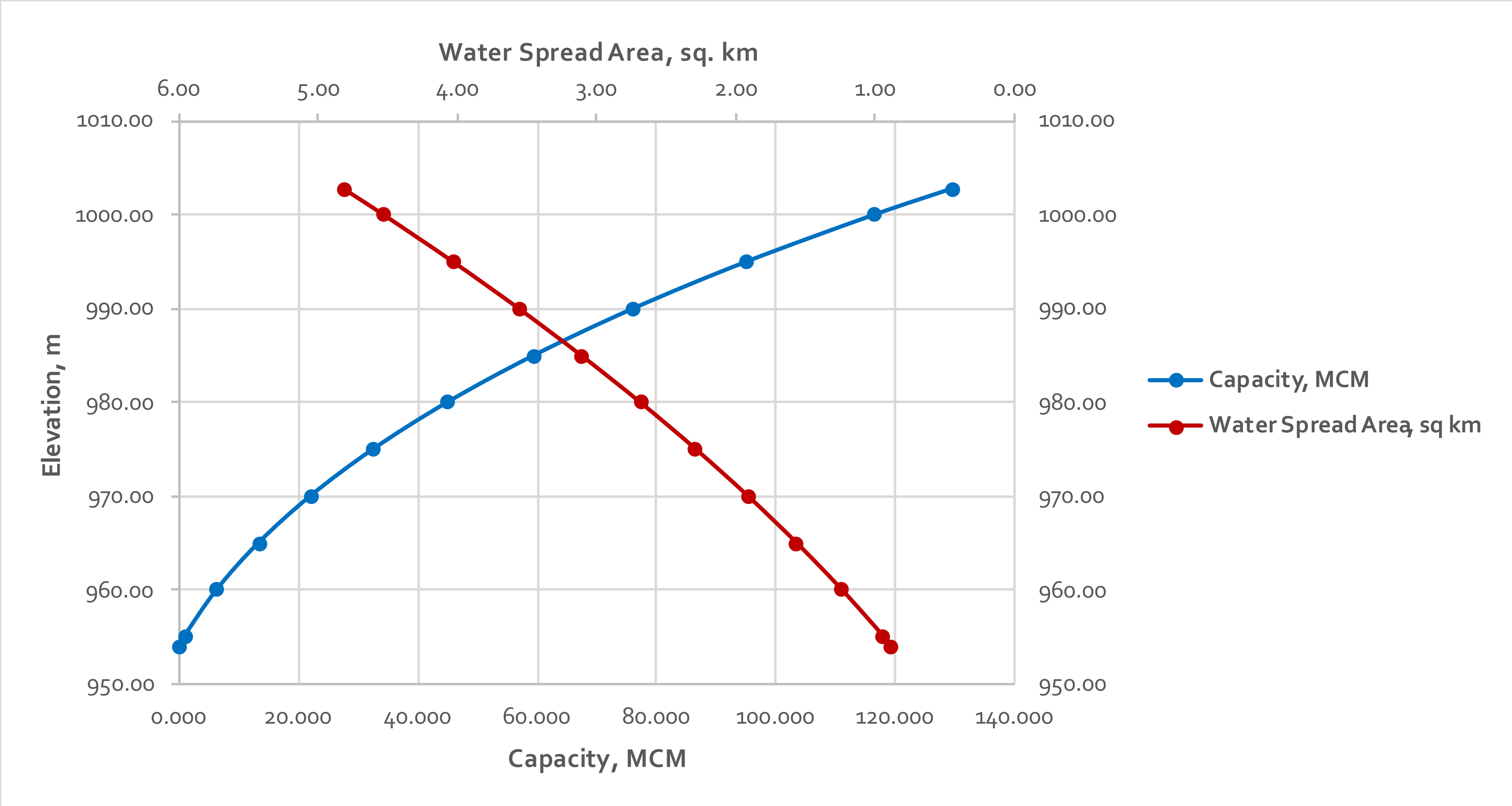


Figure 12: Elevation – Area – Capacity Curve for Sholayar Reservoir.

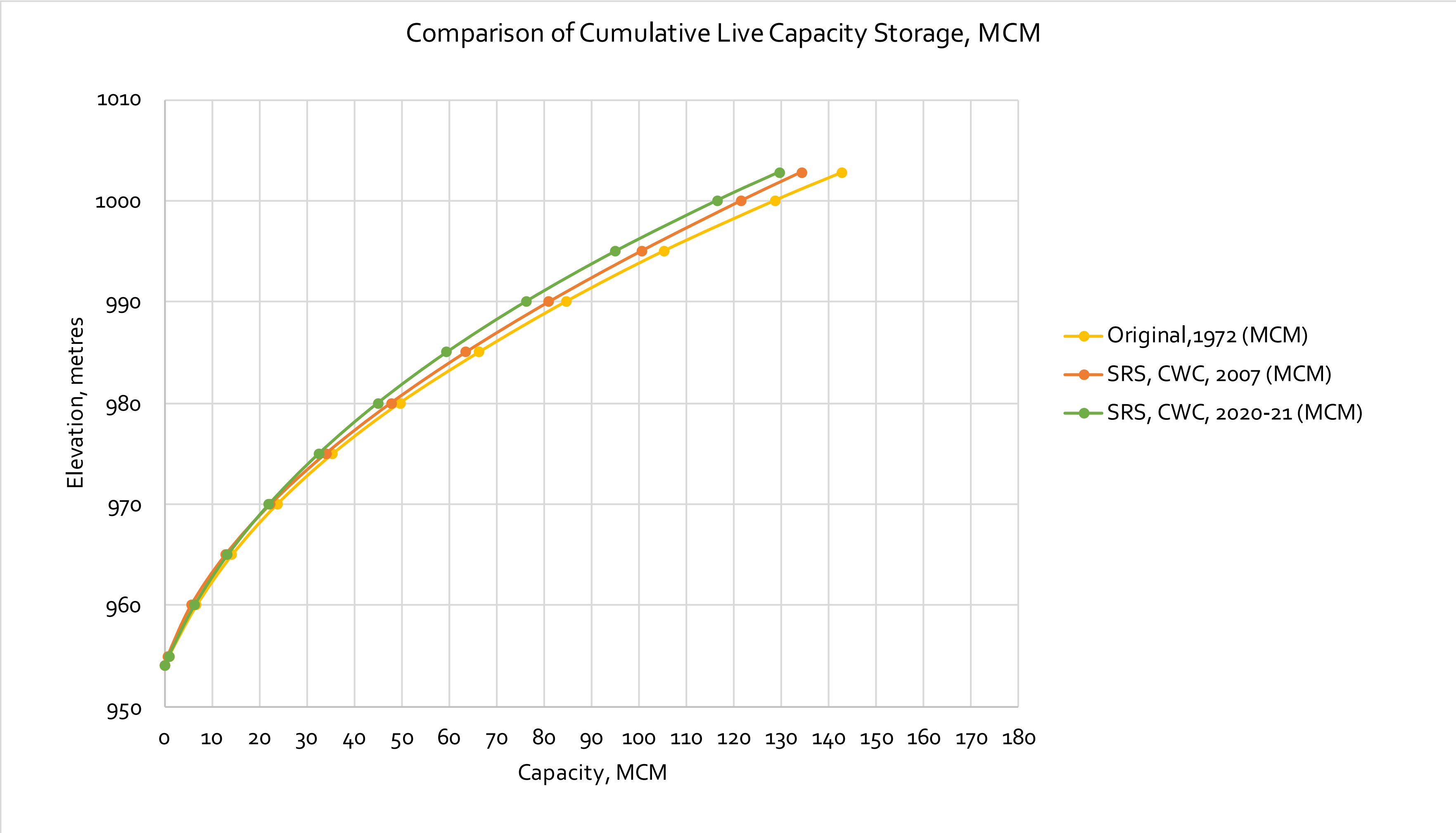


Figure 13: Comparison of Elevation - Live Storage Capacity curves (MCM) for Sholayar Reservoir.

9.4 STATUS OF LIVE STORAGE CAPACITY

The loss in live storage capacity of the reservoir due to sedimentation based on the data provided by the dam authorities and satellite remote sensing assessment (2007) are listed in Table 5.

The live storage capacity of the Sholayar reservoir has been found to be 129.49 MCM in 2020-21. According to data shared by the dam authorities, the original live storage capacity of the Sholayar reservoir was 142.88 MCM at FRL at the time of its first impoundment in 1972. This suggests a loss in live capacity of 13.39 MCM, which is 9.37% of the live capacity. Considering that the dam was built in 1972, it has been 49 years since the first assessment, resulting in an annual live capacity loss rate of 0.19%.

The CWC conducted an assessment using satellite remote sensing in 2007. This estimated the live capacity to be 134.16 MCM (in 2007), suggesting a loss of 8.72 MCM (which is about 6.10% of the original live capacity). In comparison to the current assessment and the earlier assessment by the CWC using satellite remote sensing in 2007, the present assessment suggests a reduction in storage capacity by 4.29 MCM since 2007.

Table 5: Storage capacity loss due to sedimentation as per previous surveys.

Details	Original Survey (MCM), 1972	SRS by CWC (MCM), 2007	SRS by CWC (MCM), 2020-21
Live Capacity in MCM at FRL	142.88	134.16	129.49
Loss in live capacity in MCM	-	8.72	13.39
% Live capacity loss (since 1972)	-	6.10%	9.37%
Annual % live capacity loss	-	0.17%	0.19%

10. CONCLUSIONS

The following conclusions emerge from the present study, subject to the limitations stated in following paragraphs.

- The live storage capacity of the Sholayar reservoir has been found to be 129.49 MCM in 2020-21, compared to the live storage capacity of 142.88 MCM as per the dam authorities. This suggests a loss in live capacity of 13.39 MCM, which is about 9.37% of the live capacity. Thus, the annual rate of live capacity loss is 0.19%.
- In 2007, the CWC had undertaken a satellite remote sensing survey that reported the capacity as 134.16 MCM. The annual rate of live capacity loss, considering the 2003 assessment, was 0.17%.
- Considering this, it does not suggest a significant annual rate of live capacity loss.

10.1 LIMITATIONS

As the reservoir operates in between MDDL and FRL, the satellite data is available only for this range. The satellite remote sensing-based reservoir capacity estimation works between MDDL and FRL in live storage.

- Remote sensing techniques give accurate estimate for fan shaped reservoir where there is considerable change in water-spread area with change in water level.
- Data from one water year was selected to get the required data set.
- It is difficult to ascertain the tail end of the reservoir, particularly when the level is near FRL and during rainy season. In such cases, there can be an error in ascertaining the extent of the tail end correctly.

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7. Prasojo Richard J. Boothroyd, Richard D. Williams, Trevor B. Hoey, Brian Barrett, Octria A., Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change WIREs Water. - 2020. - p. 27.

ANNEXURE A: SALIENT FEATURES

Name of Project	**Sholayar Dam**
Location:	
District	Coimbatore
State	Tamilnadu
Longitude	76° 53' 00" E
Latitude	10° 18′ 00" N
Type	Earthen Masonry dam with maximum height of 105 m above deepest foundation level.
River Tributary on which located	Sholayar river/ Tributary of Chalakudi River
Year of Completion	Completed in 1972
Total catchments up to dam site	121.68 sq. Km
Salient Levels:	
Top Bund Level	1007.36 m
Maximum Water Level	1004.32 m
FRL	1002.79 m
MDDL	954.02 m
Water Spread Area at FRL	5.24 sq. km
Designed storage capacity	
Gross Storage	152.48 MCM
Live Storage	142.88 MCM
Dead Storage	9.60 MCM
Dam	
Spillway provided Type	Lift gate type
Vent numbers	3
Vents size	42 feet x 25 feet

Disclaimer:

The data on storage capacity for the reservoir is based on the NRLD, 2023 and CWC's Compendium on Sedimentation of Reservoirs in India (2020), while other details reported here are as shared by the dam authorities.

ANNEXURE B: PHOTOGRAPH OF THE RESERVOIR

ANNEXURE C

SENTINEL-1 SAR GRD: C-BAND SYNTHETIC APERTURE RADAR GROUND RANGE DETECTED

The Sentinel-1 mission provides data from a dual-polarization C-band Synthetic Aperture Radar (SAR) instrument at 5.405 GHz (C band). This includes the S1 Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox to generate a calibrated, ortho-corrected product.

In this collection, each scene has one of 3 resolutions (10, 25, or 40 meters), 4 band combinations (corresponding to scene polarization) and 3 instrument modes. Each scene contains either 1 or 2 out of 4 possible polarization bands, depending on the instrument's polarization settings. The possible combinations are single band VV or HH, and dual band VV+VH and HH+HV:

- VV: single co-polarization, vertical transmit/vertical receive
- HH: single co-polarization, horizontal transmit/horizontal receive
- VV + VH: dual-band cross-polarization, vertical transmit/horizontal receive
- HH + HV: dual-band cross-polarization, horizontal transmit/vertical receive

Each scene also includes an additional 'angle' band that contains the approximate incidence angle from ellipsoid in degrees at every point. This band is generated by interpolating the 'incidenceAngle' property of the 'geolocationGridPoint' gridded field provided with each asset.

Each scene is pre-processed with Sentinel-1 Toolbox using the following steps:

- Thermal noise removal
- Radiometric calibration
- Terrain correction using SRTM 30 or ASTER DEM for areas greater than 60 degrees latitude, where SRTM is not available. The final terrain-corrected values are converted to decibels via log scaling (10*log10(x)).

Following the standard method for speckle correction, a median filter is applied for the VV polarization band with a radius of 10 metres that removes the speckle noise.

More details about this data can be found here: User Guides - Sentinel-1 SAR - Sentinel Online - Sentinel Online (esa.int), https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/.

Government of India

Central Water Commission

Remote Sensing Directorate

No. CWC/2024/137