

# Reservoir Sedimentation Assessment Through Remote Sensing and Hydrological Modelling

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## Abstract

Reservoir sedimentation is the gradual accumulation of incoming sediments from upstream catchment leading to the reduction in useful storage capacity of the reservoir. Quantifying the reservoir sedimentation rate is essential for better water resources management. Conventional techniques such as hydrographic survey have limitations including time-consuming, cumbersome and costly. On the contrary, the availability of high resolution (both spatial and temporal) in public domain overcomes all these constraints. This study assessed Jayakwadi reservoir sedimentation using Landsat 8 OLI satellite data combined with ancillary data. Multi-date remotely sensed data were used to produce the water spread area of the reservoir, which was applied to compute the sedimentation rate. The revised live storage capacity of the reservoir between maximum and minimum levels observed under the period of analysis (2015–2017) was assessed utilizing the trapezoidal formula. The revised live storage capacity is assessed as 1942.258 against the designed capacity of 2170.935 Mm<sup>3</sup> at full reservoir level. The total loss of reservoir capacity due to the sediment deposition during the period of 41 years (1975–2017) was estimated as 228.677 Mm<sup>3</sup> (10.53%) which provided the average sedimentation rate of 5.58 Mm<sup>3</sup> year<sup>-1</sup>. As this technique also provides the capacity of the reservoir at the different elevation on the date of the satellite pass, the revised elevation–capacity curve was also developed. The sedimentation analysis usually provides the volume of sediment deposited and rate of the deposition. However, the interest of the reservoir authorities and water resources planner's lies in sub-watershed-wise sediment yield, and the critical sub-watersheds upstream reservoir requires conservation, etc. Therefore, in the present study, Soil and Water Assessment Tool (SWAT) was used for the estimation of sediment yield of the reservoir. The average annual sediment yield obtained from the SWAT model using 36 years of data (1979–2014) was 13.144 Mm<sup>3</sup> year<sup>-1</sup> with the density of the soil (loamy and clay) of 1.44 ton m<sup>-3</sup>. The findings revealed that the rate of sedimentation obtained from the remote sensing-based methods is in agreement with the results of the hydrographic survey.

**Keywords** Reservoir sedimentation · Remote sensing · DEM · Hydrological model · SWAT model

## Introduction

Reservoirs are normally constructed across rivers and have crucial roles such as water supply, irrigation, discharge regulation, power generation and flood control (Merina et al. 2016). A reservoir is typically positioned to the end of a catchment and so collects inflows from various major rivers (Jorgensen et al. 2005). In addition, reservoirs experience a limited residence time, whilst watershed covering the reservoirs is much bigger, so it is complicated tasks of controlling the watershed with reservoirs (Randolph 2004). Reservoir sedimentation is originally caused

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as natural processes. As the hydraulic process, rivers and streams within a catchment are continuously provided with sediment from run-off, rainfall, snowmelt and the erosion of river channel, which get deposited in the reservoir (Merina et al. 2016). Whilst the key functions of dams are controlling flood and transferring water to areas with the deficit of water (Goel et al. 2002; Mukherjee et al. 2007; Wang et al. 2003), unfortunately, there are numerous reservoirs which stop performing their designed functions due to the sediment deposition (Ijam and Al-Mahamid 2012; Merina et al. 2016). Eventually, the transported sediments can be deposited at various levels of a reservoir leading to a reduction in storage capacity of the reservoir (Goel et al. 2002; Jain and Goel 2002; Vemu and Udayabhaskar 2010). Since the water flows within a reservoir with the very low velocity, the reservoirs tend to be very efficient sediment traps leading to a reduction in transport capacity and increment in the sedimentation deposition in the reservoir (Merina et al. 2016). This gradual deposition generally reduces the live storage capacity of the reservoirs and fails them to perform their intended use with passage of the time.

On the other hand, human activities and the interventions in the upstream watershed contribute to accelerated reservoir sedimentation. Although there is the fact that soil erosion results from the geomorphologic process, accelerated soil erosion is primarily favoured by human activities. Rapid population growth, deforestation, unsuitable land cultivation and uncontrolled overgrazing have caused accelerated soil erosion in the world principally in developing countries (Abebe and Sewnet 2014; Merina et al. 2016; Tamene et al. 2006). According to Merina et al. (2016), most of the reservoirs accompanying with dams on natural rivers are vulnerable to some level of sediment deposition and inflow. Approximately 40,000 large reservoirs around the world are facing sedimentation issues, and it is predicted that their total storage capacity is being lost between 0.5 and 1% per year (Merina et al. 2016). Therefore, it is essential to estimate or quantify sedimentation of the project for the whole of its life, so that appropriate conservation strategy can be implemented. Periodical capacity surveys of the reservoir assist in evaluating the rate of sedimentation and reduction in storage capacity (Jeyakanthan and Sanjeevi 2013).

There are two typical conventional methods for reservoir sedimentation estimation, including direct quantification of sediment deposition by hydrographic surveys and indirect measurement employing the inflow–outflow records of a reservoir. The two methods are non-cost-effective, cumbersome and time-consuming (Jain and Goel 2002). On the other hand, the remote sensing technology also developed significantly with the number of reservoirs in the world. Remote sensing provides synoptic coverage

of the earth surface at a regular interval at reasonable resolution since the 1970s. Since then, mapping of water bodies of significant size is being done using the satellite data. Remote sensing approach with advantages of data acquisition over a long time period has been considered as a superior method to the conventional techniques in terms of data acquisition. The advancement in the spectral, spatial and temporal resolution of remotely sensed data can effectively support in assessing the changes in the water spread area of the reservoir after deposition of sediment and sediment distribution patterns in the reservoir (Goel and Jain 1996; Jain et al. 2002; Narasayya 2013). Therefore, the remote sensing-based approach can be straightforward, cost-effective and less time required for data analysis in comparison with the conventional methods.

Application of the remote sensing techniques has become very efficient to quantify the sedimentation in a reservoir and to assess its distribution and deposition pattern. Remote sensing approach can aid in determining water spread areas at various reservoir levels, and in preparing a revised elevation–capacity curve. Afterwards, the amount of capacity lost to sedimentation will be evaluated from the comparison of the original and revised elevation–capacity curves (Vishwakarma et al. 2015; Merina et al. 2016). When it is combined over a range of elevations using multi-date satellite data enables computing volume of storage lost due to sedimentation. Recently, with the presence of high-resolution remotely sensed data, the reservoir sedimentation assessment using the remote sensing approach is becoming acceptable and recognition. Thereby, there are numerous studies making efforts to apply the remote sensing-based approach to study sedimentation issues such as Smith et al. (1980), Vibulsresth et al. (1988), Jagadeesha and Palnitkar (1991), Goel and Jain (1996), Jain et al. (2002), Goel et al. (2002), Jain and Goel (2002), Rathore et al. (2006), Mukherjee et al. (2007), Sumantyo et al. (2012), Mandwar et al. (2013), Narasayya (2013), Jeyakanthan and Sanjeevi (2013), Yeo et al. (2014) and Merina et al. (2016).

Regarding using hydrological modelling for reservoir sedimentation assessment, previous studies have mostly concentrated on the deposition of sediment in larger reservoirs. The two most common empirical methods are the area increment method (AIM) (Cristofano 1953) and the empirical area reduction method (EARM) (Borland and Miller 1960), which were developed on the basis of siltation process of dead storage from 30 reservoirs. In the context of the shortage of studies on sediment deposition in a small reservoir, Dendy (1982) introduced the approach of spatial bottom sediment distribution in reservoirs of large storage capacity from 20,000 m<sup>3</sup> to 1.7 M m<sup>3</sup>. Michalec (2008) developed Dendy's approach for smaller reservoirs at Zeslawice on the River Dlubnia. In the context of

limitation of techniques, especially models, and studies for reservoir sedimentation, the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) model developed in the early 1990s by the US Department of Agriculture, Agricultural Research Service (USDA-ARS) overcomes all these limitations to provide great potential for reservoir sedimentation using modelling approach. Recently, there are several attempts using SWAT for reservoir sedimentation issues. These studies include Mishra et al. (2007), Xu et al. (2009), Setegn et al. (2010), Jain et al. (2010), Ndomba and van Griensven (2011), Betrie et al. (2011), Ayana et al. (2012), Ijam and Tarawneh (2012) and Tyagi et al. (2014). The previous studies have proven that the SWAT model has great potential for estimate run-off and sediment yield assessment.

Generally, in the literature either reservoir sedimentation deposition studies are reported or sediment yield modelling. A very few attempts have been made to assess sediment yield and sedimentation altogether. It is well reported that all reservoirs are subjected to sedimentation and the problem of sedimentation cannot be totally stopped; however, it can be controlled by various means on the upstream reservoir watershed. Therefore, there is a need to understand the behaviour of the upstream catchment towards sediment yield along with reservoir sedimentation. Keeping the importance of both in mind, in the present study, sediment deposition in the Jayakwadi reservoir located on Godavari River was assessed utilizing the remote sensing approach, and sediment yield of the catchment was evaluated using SWAT model.

## Study Area Description and Data Used

### Study Area

The Jayakwadi (Nathsagar) reservoir is one of the largest multipurpose projects in the Indian state of Maharashtra. The reservoir is located on Godavari River at the site of Jayakwadi village in Paithan taluka of Aurangabad District in Maharashtra State of India. The water is mainly used to irrigate agricultural land in the drought-prone Marathwada region of the state. It also provides water for drinking and industrial usage to nearby towns and villages and to the municipalities and industrial areas of Aurangabad and Jalna Districts. The surrounding area of the dam has a garden and a bird sanctuary. The location of the reservoir and its catchment is shown in Fig. 1.

Jayakwadi is one of the largest earthen dams in Asia. Its height is 41.30 m and length is 9998 m (approx.). The total storage capacity at full reservoir level (FRL) of 463.906 m is 2909 Mm<sup>3</sup>, and effective live storage capacity between FRL and maximum draw down level (MDDL) is

2171 Mm<sup>3</sup>. The MDDL of the reservoir is at reduced level of 455.524 m. The designed dead storage capacity is 738.08 Mm<sup>3</sup>. The total catchment area of up to Jayakwadi dam is 21,750 km<sup>2</sup>. As per hydrographic survey report of year 1999, the gross capacity was reduced to 2659.24 Mm<sup>3</sup>; however, the remaining live storage reduced to 2076.78 Mm<sup>3</sup> (IWRIS—[www.india-wris.nrsc.gov.in](http://www.india-wris.nrsc.gov.in)). The reservoir live capacity was reassessed through remote sensing approach by the Central Water and Power Research Station, Pune, in the year 2003 as 1942.81 Mm<sup>3</sup>.

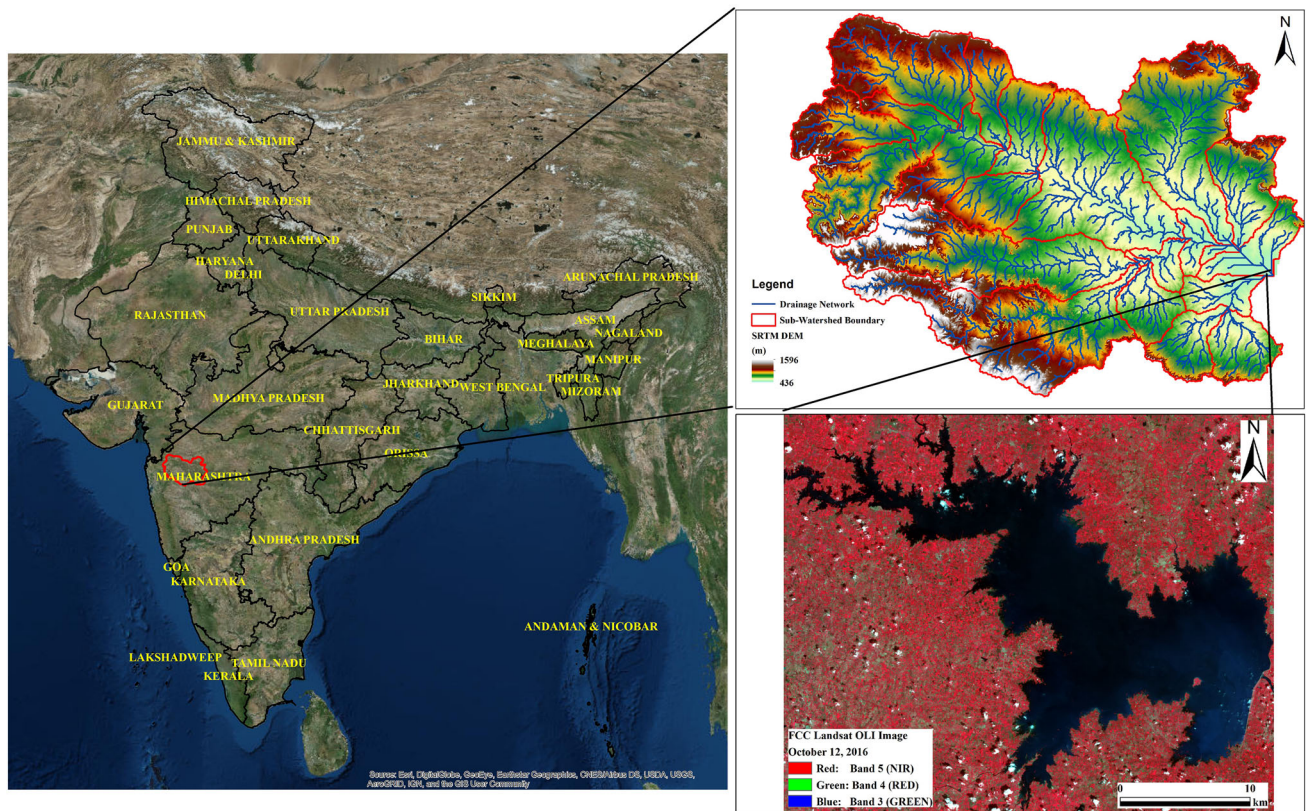
### Date Used for Reservoir Sedimentation Assessment Analysis

The primary data to assess the sedimentation through remote sensing are the earth observing multi-spectral satellite data. Therefore, in the study, Landsat 8 Operational Land Imager (OLI) satellite data for assessing sedimentation in Jayakwadi reservoir were used. The major advantages of the Landsat series data are: available free of cost in public domain, reasonable spatial (30 m) and temporal (16 days) resolution. The characteristic of Landsat 8 OLI is given in Table 1. There were 8 cloud-free georeferenced images captured by various dates of pass of satellite from October 2015 to October 2016, which were downloaded from USGS website (<http://earthexplorer.usgs.gov>). These images were used for extracting different water spread at different dates with maximum variation in the water level. The acquired remote sensing data for the year 2015–2016 are given in Table 2. In order to calculate the live capacity of the reservoir from MDDL to FRL, the data of September 29, 2017 was also used as the reservoir was nearly at FRL on that day.

However, to estimate the change in capacity or volume of sediment deposited, the original elevation–area–capacity curve along with the water level on the selected dates for the year 2015–2016 was procured from the Office of Executive Engineer, Jayakwadi Irrigation Division Nath Nagar (North), Paithan, Aurangabad, is given in Table 3.

### Date Used for Sediment Yield Modelling

To set up the SWAT hydrological model to estimate sediment yield, various data sets from different sources were used. The flow in the river or on the surface, which carries the sediments along with it, is governed by the topography. To extract the topographic features such as slope, flow direction and flow accumulation, the Shuttle Radar Topography Mission (SRTM) digital elevation model available at 30 m resolution was used (<https://lta.cr.usgs.gov/SRTM>). The data were downloaded from USGS website (<http://earthexplorer.usgs.gov>). However, the vegetative provides the resistance to the flow generated on the



**Fig. 1** Location of Jayakwadi reservoir in India and reservoir as seen from Landsat 8 OLI image with the catchment

**Table 1** Characteristic of Landsat 8 OLI data (Barsi et al. 2014)

	Band name	Bandwidth ( $\mu\text{m}$ )	Resolution (m)
Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) Launched on 11 February 2013	Band 1 Coastal	0.43–0.45	30
	Band 2 Blue	0.45–0.51	30
	Band 3 Green	0.53–0.59	30
	Band 4 Red	0.64–0.67	30
	Band 5 NIR	0.85–0.88	30
	Band 6 SWIR 1	1.57–1.65	30
	Band 7 SWIR 2	2.11–2.29	30
	Band 8 Pan	0.50–0.68	15
	Band 9 Cirrus	1.36–1.38	30
	Band 10 TIRS 1	10.6–11.19	100
	Band 11 TIRS 2	11.5–12.51	100

surface. The land use/land cover (LULC) of the year 2005 was obtained from Indian Space Research Organisation—Geosphere Biosphere Program project on “Land Use Land Cover dynamics and impact of Human Dimension in Indian river basins project”, which is available at 1:250,000 scale as shown in Fig. 2. The soil properties and type also play important role in sediment transport. The

soil map was extracted from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) data available at 1:50,000 scale as shown in Fig. 3.

Climate/weather data are among the most important data required for the hydrological simulation using SWAT model. The model was forced by the meteorological parameters such as daily rainfall, temperature, wind speed,

**Table 2** Landsat 8 OLI data download for the year 2015–2017











Satellite	Path/row	Date of pass
Landsat 8 OLI	146-47	26 October 2015
Landsat 8 OLI	146-47	11 November 2015
Landsat 8 OLI	146-47	29 December 2015
Landsat 8 OLI	146-47	30 January 2016
Landsat 8 OLI	146-47	15 February 2016
Landsat 8 OLI	146-47	18 March 2016
Landsat 8 OLI	146-47	28 October 2016
Landsat 8 OLI	146-47	29 September 2017

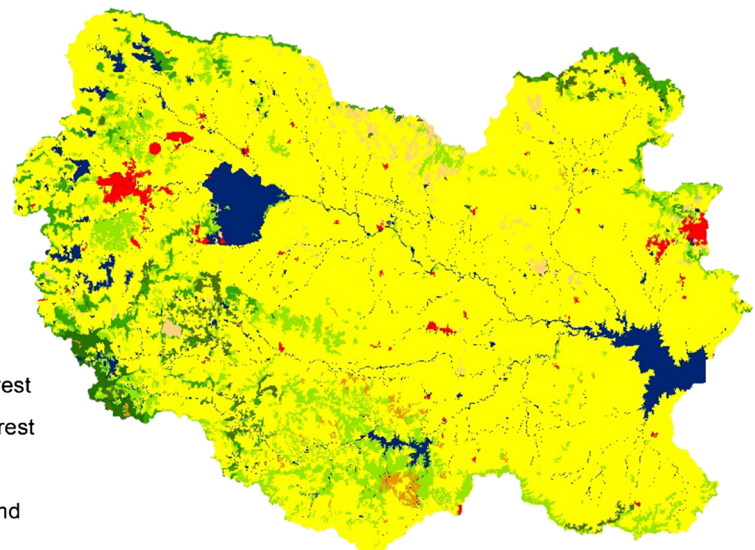
**Table 3** Designed elevation–area–capacity curve of the Jayakwadi reservoir

Elevation (m)	Area (Mm <sup>2</sup> )	Capacity (Mm <sup>3</sup> )
463.906	397.61	2170.935
460.096	264.76	918.056
459.410	243.85	749.475
458.724	222.96	580.891
458.876	227.60	618.354
458.419	214.59	519.386
456.895	174.65	223.164
456.667	169.77	185.51
456.651	168.77	183.00
455.915	137.94	68.977

solar radiation and relative humidity. The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data on these parameters for the period of 1979–2014 were obtained from the <http://swat.tamu.edu/> in SWAT format.

**Fig. 2** Land-use land-cover map of the study watershed**Legend****LULC Map****Classes**

	WATR
	Urban
	Shrab Land
	Fallow Land
	Plantation
	Mixed Forest
	Everigreen Forest
	Deciduous Forest
	Barren Land
	Agricultural Land

**Methodology**

The present study is divided into two sections as per its objectives: assessment of reservoir sedimentation using remote sensing approach and estimation of sediment yield using hydrological modelling approach. For the reservoir sedimentation assessment, the data of Landsat 8 OLI for different dates were analysed and the capacity was estimated using the trapezoidal formula. The change in reservoir capacity between two time periods is regarded as volume of sediments deposited. However, for the modelling of sediment yield using hydrological modelling, the most commonly used SWAT model was used. SWAT is mainly or extensively used for rainfall run-off modelling. A very few studies with the emphasis on sediment yield were found in the literature. The overall methodology adapted in the present study is shown in Fig. 4.

**Reservoir Sedimentation Assessment**

For reservoir sedimentation assessment, the methodology applied for the study relates remotely sensed data processing, estimation of the water spread area and computation of reservoir capacity at each elevation (on the date of pass of the satellite). Finally, the computation of cumulative capacity, revised elevation–capacity curve and volume of sediment deposited were carried out. These steps are discussed as the following.

**Remotely Sensed Data Processing**

The Landsat 8 OLI sensor captures reflected solar energy, converts these data to radiance and then rescales these data into an 8-bit digital number (DN) with a range between 0

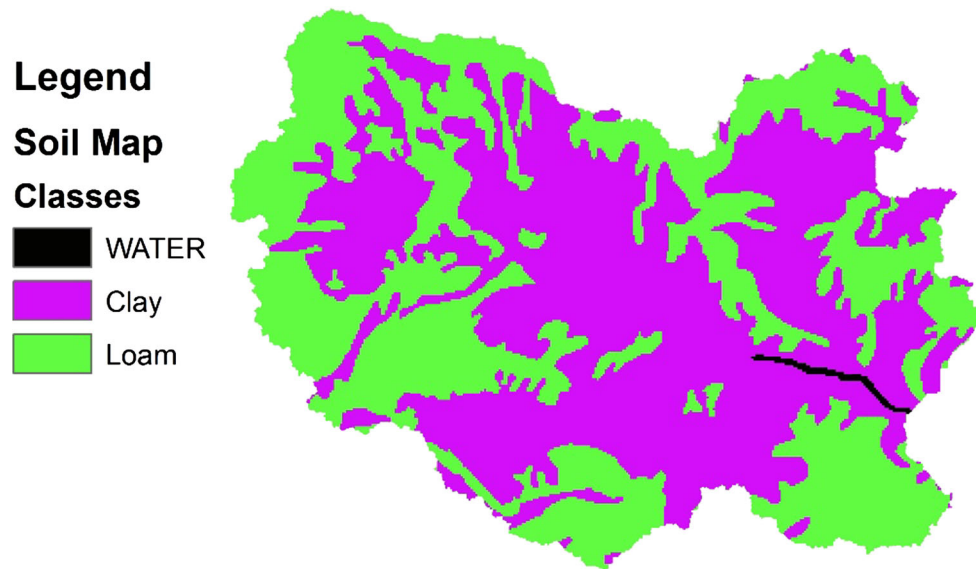


Fig. 3 Soil texture map of the study watershed

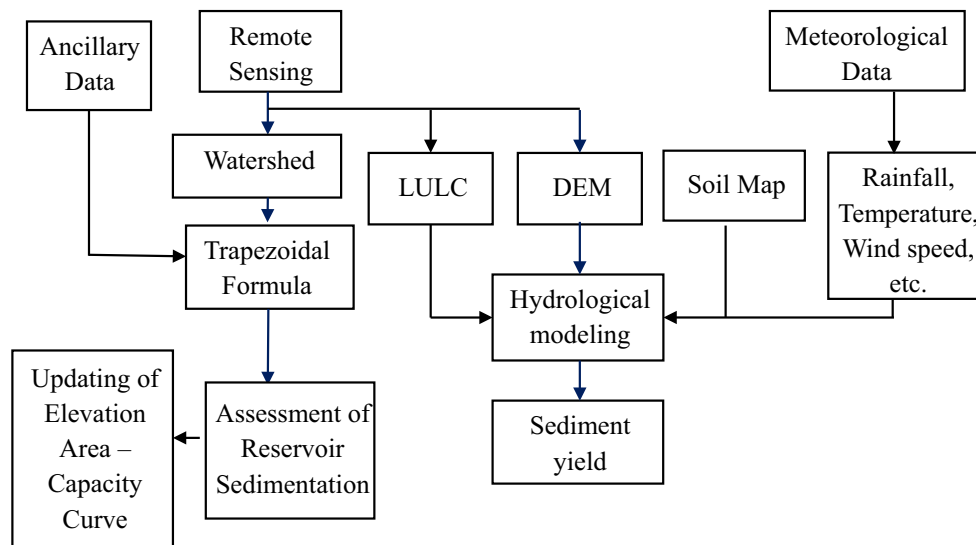


Fig. 4 Overall methodology flow chart

and 255. The ERDAS IMAGINE enables us to convert these DNs to reflectance applying two steps. The first step is to convert the DNs to radiance values utilizing the bias, and gain values specific to the individual scene. The second step is to convert the radiance values to reflectance values. It is to be noted that for the present analysis the level 2 product of Landsat 8 which directly gives reflectance has been used.

#### Estimation of the Water Spread Area

The satellite imagery was analysed to determine the water spread area. Knowing the water spread area from a particular image, the periphery of the water spread area was obtained using image processing techniques. Identification of water spread area includes three main stages such as surface water body's extraction, separation of area of interest and estimation of water spread area.

## Surface Water Bodies Extraction

For surface water bodies' extraction, it is required to identify the number of water pixels. Though the spectral signature of water is quite distinct from other land uses like vegetation, built-up area and soil surface, identification of water pixels at water/soil interface is very difficult and depends on interpretative ability of analyst. In order to identify water pixels, the following steps are performed:

Normalized difference water index (NDWI) is used to monitor changes related to water content in water bodies, using green and NIR wavelengths, defined by (McFeeters (1996)) the following formula:

$$NDWI = (Green - NIR) / (Green + NIR)$$

where Green is a band that encompasses reflected green light and NIR represents near-infrared radiation.

The NDWI image was produced in which generally the water features have positive values, whilst soil and other features have negative values. Image processing software, ERDAS IMAGINE, can easily be configured to delete the negative values and then water pixels can be available for analysis. It is to be noted that it is not necessary that all the positive values will always be water. With time, generally, the water reflectance in the satellite image changes; therefore, it is necessary to verify the pixels selected as water. It may sometimes result in overestimation or underestimation of water spread. Further, thresholding technique can be used for extracting water spread estimation. In the present study, the threshold value for different dates varies from  $-0.032$  to  $-0.042$  on NDWI image.

## Separation of Area of Interest

Since the size of full scene was very large and the area of interest is only the reservoir water spread area, the reservoir area and its surroundings were separated out from the full scene image in all data sets. This task was done through a utility named "Extract by Mask" under Spatial Analyst tool in ArcGIS software. The water spread area, extracted from the Landsat 8 OLI image obtained on September 29, 2017 which corresponds to FRL, was used to mask out the area of interest and water pixels in the reservoir area. This has been done to maintain the analysis domain constant for all the images and avoid the stray or discontinuous pixels.

## Estimation of Water Spread Area

Once water pixels for the area of interest are determined for Jayakwadi reservoir, water spread area of 8 cloud-free dates of pass (Table 2) was estimated utilizing the below equation:

$$\text{Water spread area} = \frac{\text{No. of Water pixels} * \text{Pixel Area}}{1000000}$$

The satellite image acquired in the present study, i.e. Landsat, has a resolution of 30 m. Hence, pixel area is  $30 \text{ m} * 30 \text{ m}$ .

## Computation of Reservoir Capacity

The capacity of reservoir between two successive reduced levels (RLs) and water levels was calculated using trapezoidal formula given below as:

$$\text{Volume } V = H * (A1 + A2 + \sqrt{A1 * A2}) / 3,$$

where  $H$  is the difference between RLs or altitude (height) interval;  $A1$  and  $A2$  are water spread areas at RL (1) and RL (2) of respective dates.

Progressive volumes were computed and compared with the design volumes for the same levels. The reduction in volume was attributed to the estimation of present storage capacity and capacity loss due to sedimentation.

## SWAT Model for Sediment Yield Estimation

### Description of SWAT Model

SWAT is a physically based, conceptual, continuous-time river basin simulation model that provides a better understanding of sediment transport and deposition processes by overland flow and able reasonable estimation and forecasting. Sediment yield is the sum of the sediments produced by overland flow, gully, and stream channel erosion in a watershed. The key factor handling sediment yield generally is the transport volume of run-off (Mutchler et al. 1988). Sediment transport in the channel network is a function of degradation and aggradations (Neitsch et al. 2005). The current version of the model routes the maximum amount of sediment in a reach as a function of the peak channel velocity and estimates sediment yield for each hydrological response unit using modified universal soil loss equation (MUSLE) (Williams 1975).

The watershed is divided into sub-watersheds which are later subdivided into one or numerous homogeneous hydrological response units (HRUs) with comparatively unique combinations of LULC, soil and topographic conditions (Ayana et al. 2012). The hydrological component of the model measures a soil–water balance at each time step depended upon daily quantity of precipitation, run-off, evapotranspiration, percolation and baseflow. The estimation of sediment yield is calculated using MUSLE equation at the HRU level, and the sediment yield will be summarized in each sub-watershed. The simulated variables (water, sediment, nutrients and other pollutants) are routed

**Table 4** Major land-use classes in the study area watershed as per SWAT model domain

No.	Land-use category	Code	Area (ha)	% Watershed area
1	Residential	URBN	301,321	1.232
2	Agricultural land-row crops	AGRR	19,346,134	79.088
3	Orchard	ORCD	15,493	0.063
4	Forest-mixed	FRST	334,398	1.367
5	Forest-deciduous	FRSD	681,187	2.785
6	Forest-evergreen	FRSE	157,020	0.642
7	Range-brush	RNGB	1,873,714	7.66
8	Pasture	PAST	287,453	1.175
9	Water	WATR	1,335,077	5.458
10	Barren	BARR	129,793	0.531
	Total		24,461,590	100

through the stream network to the watershed outlet (Ayana et al. 2012).

### Model Inputs

The basic spatial input data sets used by the model include the digital elevation model (DEM), land-use/land-cover data, soil data and climatic data. The DEM is one of the key inputs of the SWAT model for understanding the topography of the watershed. Topographic features can be identified by a DEM in which the elevation of any point in a specified area at a given spatial resolution is described. In this study, a SRTM DEM of 30 m spatial resolution was used to delineate the watershed boundary and examine the drainage patterns of the land surface terrain. Topographic parameters, including slope length, slope gradient and stream network characteristics, namely slope length and width, channel slope, were extracted from the DEM. Most importantly, the slope per cent map was generated using the DEM, which was further used as an input for HRU generation. The slope per cent map was reclassified as per the SWAT model requirements. The LULC is one of the most crucial factors affecting run-off, surface erosion and evapotranspiration within a watershed during replication (Neitsch et al. 2005). The ISRO-GBP LULC map as shown in Fig. 2 was reclassified to the nearest class in the SWAT model domain as presented in Table 4. In a similar guideline, the soil data set from NBSS & LUP (Fig. 3) was applied for soil layers by integrating soil data sets with the SWAT database file. In the model, the soil data were reclassified and clipped to be fitted the existing delineated watersheds in a manner similar to that used for the land-use data sets.

To force the model, weather data, such as precipitation, temperature, wind speed, evaporation, solar radiation and relative humidity, are required. A built-in weather data set contains simulated weather data input in the USA. In the present study, the custom weather generator was applied, since the study site is outside the USA. In the present study,

daily temperature, precipitation, wind, relative humidity and solar radiation (36 years) data were derived from the NCEP CFSR data for period from 1979 to 2014 for 28 grids within the catchment area.

### Model Set-up

The ArcSWAT framework was applied for setting up and parameterizing the model. A DEM was loaded into the SWAT model. A polygon in grid format was used to extract the interest area, to delineate the watershed boundary and to generate the stream networks for the study area. The outlet for the analysis is taken as Jayakwadi dam. For this study, the minimum threshold area of 5000 ha was used to divide the watershed into sub-watersheds. The LULC and soil maps in grid format were also imported to the model, and these maps were overlaid and analysed to attain a distinctive combination of land use, soil and slope for each watershed to be modelled. In this study, multiple HRUs with 25% land use, 25% soil and 25% slope thresholds were utilized. The threshold values were set to remove minor classes of LULC, soil and slope within sub-watershed to generate a maximum of 10 HRUs with unique combinations of LULC/soil/slope within a sub-watershed, to meet the requirement of the SWAT user manual. The data of daily maximum and minimum temperature and daily rainfall were organized in the required file format, .dbf database file, and imported into the model. Finally, the sediment yield of the sub-watersheds which are contributing to reservoir is added to find the total sediment yield of the reservoir.

## Results and Discussion

### Reservoir Sedimentation Assessment

The surface water bodies extraction task was done for the full period (2015–2016) using the NDWI technique as



discussed in Methodology section. Figure 5 shows the false colour composite (FCC) and the extracted water spread on each day of satellite pass along with the variation in water spread throughout the water year 2015–2016.

The water spread area of the reservoir was calculated using remotely sensed data. The NDWI was calculated with the help of satellite data using thresholding method to define water spread area in a reservoir for different time intervals. In addition, using the elevation and corresponding water spread area, the capacity of reservoir between two successive RLs and water levels was calculated using trapezoidal formula (Table 5) as given in Methodology section. Once the reservoir capacities between two successive RL were calculated, the cumulative capacity for the water year 2015–2017 was thus estimated. During the time period of analysis, the water level variation was from 455.368 m (18 March 2016) to 463.906 m (29 September 2017). The cumulative live storage capacity between these two reservoir levels could be estimated; and the difference between the original and estimated cumulative capacity represented the loss of capacity due to sedimentation in the live zone of the reservoir as given in Table 5.

The table also presents the estimated volume on different dates used to calculate the sediment deposition in the reservoir. The revised live storage capacity of Jayakwadi reservoir between the lowest water level observed during the period of analysis 455.368 m and FRL 463.906 m was estimated to be 1942.258 Mm<sup>3</sup> for the year 2015–2017 compared to original live storage capacity of 2170.935 Mm<sup>3</sup>. Therefore, there is a loss of 228.677 Mm<sup>3</sup> (10.53%) live storage capacity attributed to the sediment deposition in the zone of study. Hence, the average annual loss was 5.58 Mm<sup>3</sup> year<sup>-1</sup> (0.26%) in live storage within a period of 41 years (from 1976 to 2017) which matched with the limits.

The results of the present analysis were compared with the hydrographic survey carried out during the period 2012–2013 as given in Table 6. It was found that the estimated rate of sedimentation is slightly higher (5.58 Mm<sup>3</sup> year<sup>-1</sup>) than the rate estimated in the year 2012–2013 (4.84 Mm<sup>3</sup> year<sup>-1</sup>). This slight change in sedimentation rate can possibly be attributed to sensitivity in the determination of the water spread area applying remote sensing techniques. The mixing of pixels having a large rate of land and a smaller proportion of water, such as those around the periphery of the reservoir, may also affect the results (Jain et al. 2002). Moreover, the sedimentation rate derived from the survey was based on the capacity of the reservoir at an elevation of 463.23 m which was a bit lower than the FRL (463.906 m). This slight difference in the elevation may also impacted on these results of sedimentation rate.

The storage capacities estimated for different durations were plotted against the corresponding elevations to develop the revised elevation–capacity curve. To assess the sedimentation, the results obtained for the water year 2015–2017 were compared with the original data obtained by the hydrographic survey method in the year 1975–1976. The comparison of the current findings with the designed is presented in Fig. 6. It is clear that the difference between the lines plotted for water year 1975–1976 and 2015–2017 shows the decrease in the capacity of water storage caused by sediment accumulation in the reservoir. Figure 6 also describes the updated elevation–capacity curve up to the year 2017 in comparison with the designed curve of the year 1975–1976. It is clear from the graph that the updated capacity experienced a little decrease compared to the designed capacity within the elevation from 455 m to 460 m. By contrast, with the elevation greater than 460 m up to 463.906 m (FRL), the capacity tended to decrease with higher rate. For the current year, the peak elevation reached to 463.906 m (FRL) with corresponding live storage capacity of 1942.258 Mm<sup>3</sup>.

### Sediment Yield of the Catchment

The SWAT model was set up as described in Methodology section; it provided information on the annual sediment yield from the reservoir catchment during a period of 36 years (from 1979 to 2014). Total sediment coming to the basin during this period of time was 681,379,873.25 ton. The sediment included two types of soils, namely clay and loamy, with mean density of 1.44 ton m<sup>-3</sup>. Based on such data, the sediment yield from the reservoir catchment was calculated. The average sediment yield obtained from the SWAT model was 13.144 Mm<sup>3</sup> year<sup>-1</sup>. However, the sediment yield obtained from the model was quite higher in comparison with the results obtained from remote sensing approach (5.58 Mm<sup>3</sup> year<sup>-1</sup>). It is obvious that the sediment yield from the catchment will always be high as compared to sedimentation rate, as it is not necessary that all the sediments coming to reservoir get deposited in the reservoir. Some fraction of sediments may always pass through the dam body out of the reservoir. But, still the estimate sediment yield through modelling is very high; therefore, it is recommended to calibrate the SWAT model to identify sensitive parameters to improve model performance. Moreover, at present the model was developed based on the reanalysis data on meteorological parameters, so there is a need to validate the model using field-observed data to robustly prove the accuracy of the results and the effectiveness of the approach. Furthermore, an analysis on trap efficiency of the reservoir can be done using these two approaches.

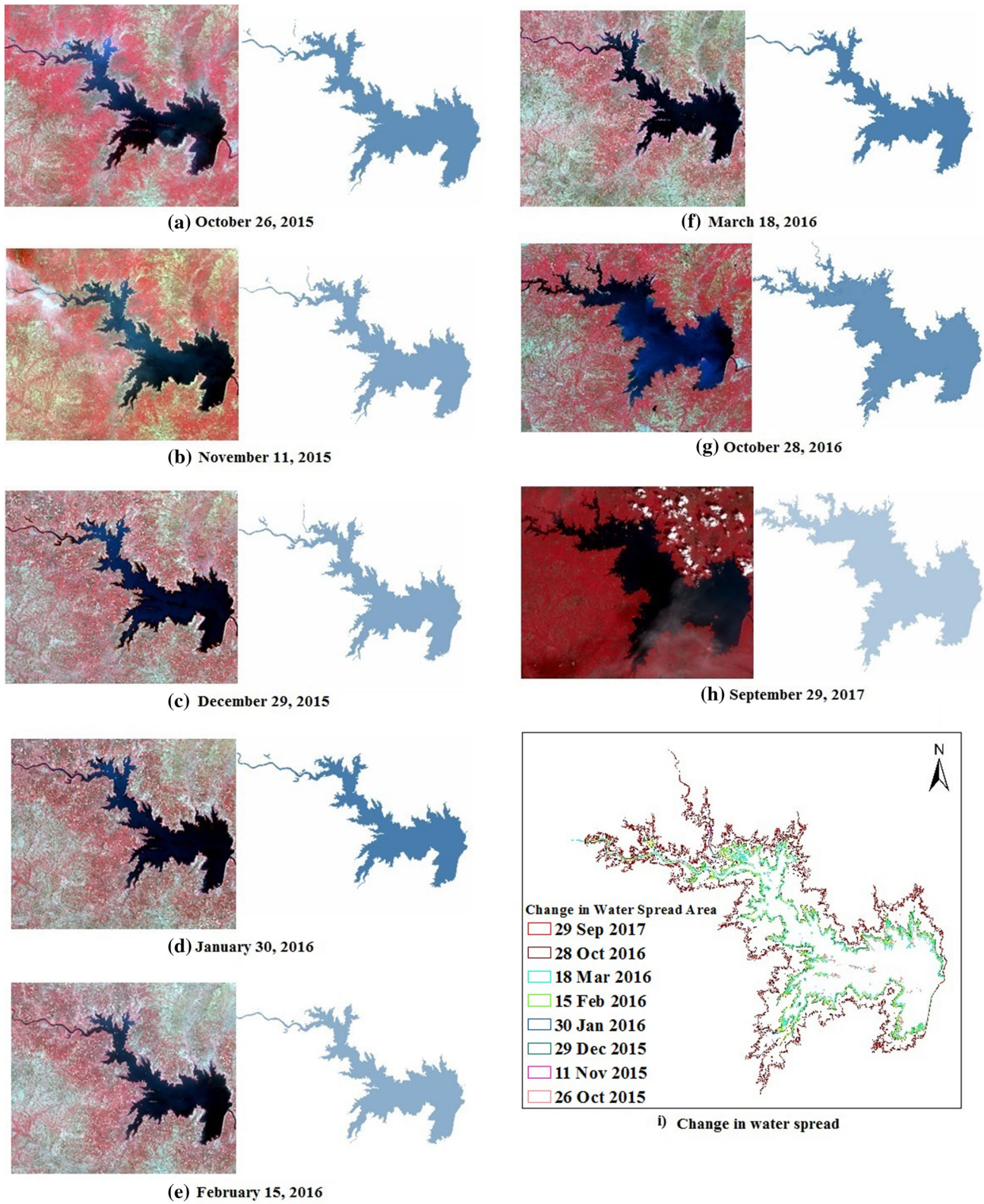


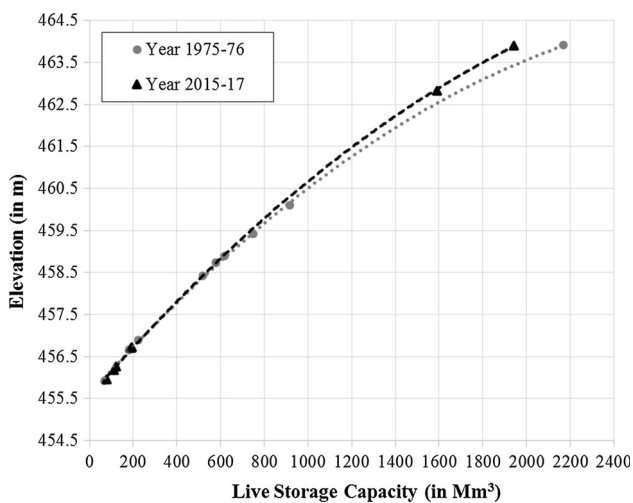
Fig. 5 FCC and water spread area of selected day during the period of 2015–2017 of the Jayakwadi reservoir

**Table 5** Comparison between designed and estimated—water spread area and capacity of Jayakwadi reservoir

Original as per design 1975–1976			Obtained by remote sensing technique 2015–2017			
Elevation (m)	Area (Mm <sup>2</sup> )	Capacity (Mm <sup>3</sup> )	Date of satellite pass	Elevation (m)	Area (Mm <sup>2</sup> )	Capacity (Mm <sup>3</sup> )
463.906	397.61	2170.935	29/9/2017	463.906	341.221	1942.258
460.096	264.76	918.056	28/10/2016	462.830	312.114	1590.880
459.410	243.85	749.475	29/12/2015	456.732	155.618	192.163
458.724	222.96	580.891	11/11/2015	456.714	158.360	189.337
458.876	227.60	618.354	30/01/2016	456.270	145.603	121.877
458.419	214.59	519.386	26/10/2015	456.188	141.349	110.113
456.895	174.65	223.164	15/02/2016	456.960	139.370	78.111
456.667	169.77	185.51	18/03/2016	455.368	124.655	–
456.651	168.77	183.00	–	–	–	–
455.915	137.94	68.977	–	–	–	–

**Table 6** Comparisons of results of hydrographic survey with results obtained from remote sensing approach for the Jayakwadi reservoir

Description	Hydrographic survey		Present analysis 2015–2017
	Original 1975–1976	2012–2013	
Live storage capacity (Mm <sup>3</sup> )	2170.935	1991.987	1942.258
Average annual (Mm <sup>3</sup> year <sup>-1</sup> )	–	4.84	5.58
Elevation (m)	463.906	463.23	463.906



**Fig. 6** Comparisons of the capacity curve of 2015–2017 with the previously obtained results

### Conclusions

The assessment of reservoir sedimentation was carried out using remote sensing approach to obtain the revised live capacity of the year 2015–2017 at FRL. The estimated revised live storage capacity of the reservoir was found to be 1942.258 Mm<sup>3</sup> against the original live storage capacity of 2170.935 Mm<sup>3</sup>. The total loss of reservoir capacity from 1975–1976 to 2015–2017 was estimated as 228.677 Mm<sup>3</sup>, or 10.53 in percentage in comparison with the original

designed capacity. Based on these results, the average annual loss of live storage within the period of 41 years (from 1976 to 2017) was identified as 5.58 Mm<sup>3</sup> year<sup>-1</sup> (0.26% year<sup>-1</sup>). Meanwhile, field observation data through hydrographic survey provided a sedimentation rate of 4.84 Mm<sup>3</sup> year<sup>-1</sup> for the period of 2012–2013. The slight change in sedimentation rate attained from remote sensing approach can be clarified on the basis of accuracy in the identification of water spread area and the misclassification of water pixels with the land around the periphery of the reservoir. However, the utilization of enhanced (spatial and temporal) resolution remotely sensed data can solve these issues to some extent. The slight difference in elevation (463.23 m in the year 2012–2013 and 463.906 m in the year 2015–2017) of the reservoir when obtaining the reservoir capacity also contributed to this difference in the two results. In addition, the updated elevation–capacity–area curve for the reservoir up to the year 2017 was also derived. Sediment yield from the reservoir catchment using hydrological modelling (SWAT) was also estimated. The sediment yield obtained from the model was 13.144 Mm<sup>3</sup> year<sup>-1</sup>. It is noted that density of sediment coming to the reservoir is assumed to be 1.44 ton m<sup>-3</sup>. It is to be noted that the estimate sediment yield through hydrological modelling is higher than the sedimentation rate obtained by the remote sensing approach. It may be possible that the sediment yield from the catchment higher than such analysis, as all the sediments coming from the catchment will not get deposited in the reservoir. Still, the

sediment yield estimated by the model is on higher side; therefore, it is recommended to calibrate and validate the model through the field-observed data.

The application of remote sensing approach is not only a cost-effective method for estimating live storage capacity, loss due to sedimentation compared to conventional techniques, but also provides a reasonable accuracy for the scope of reservoir sedimentation estimation. To improve the accuracy of the reservoir sedimentation estimation, it is suggested that hydrographic surveys should be carried out at longer intervals, and the remote sensing-based sedimentation surveys may be conducted at shorter intervals, as both methods complement each other. However, there are some disadvantages of the remote sensing-based approach for reservoir sedimentation assessment. In particular, remote sensing methods enable to extract information of the reservoir capacities in the water level fluctuation zone—the live storage of the reservoir. Below this zone, for example in the dead load zone, the capacity of the reservoir can only be obtained from the most recently conducted hydrographic survey, but not from remote sensing data. The remote sensing approach is also sensitive to accurate identification of the water pixels. Therefore, the use of high spatial resolution data is recommended.

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