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Assessment of Reservoir Sedimentation using RS and GIS techniques - A case study of Kabini Reservoir, Karnataka, India

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Abstract - *Reservoir sedimentation is an accepted occurrence. The reduction in storing capacity with sediment deposits in a reservoir over a period of time can be interconnected with the decline in the water spread area at different elevations. This study illustrates the assessment of reservoir sedimentation using RS and GIS. The area capacity curve of the year 1974 (impoundment) is now used as a base for sedimentation assessment for the year 2013-14. This will help us to evaluate sedimentation over a period of time. In this study, digital processing is carried out using the ERDAS image processing software. The Normalized Difference Water Index has been used to delineate open water features and to improve the presence of water surface in satellite imagery of the Kabini Reservoir. The water spread area of the reservoir at a particular elevation on the date of the passing of the satellite is used to develop an elevation-area curve. Then a linear interpolation/ extrapolation technique has been used to estimate the water spread area of the Kabini Reservoir at various elevations. Further, these areas were used to compute the live storage capacity of the reservoir between two elevations by using the Prizmoidal formula.*

The revised capacity of the reservoir is then compared with the original capacity of the year 1974 so as to give the loss in capacity from 1974 to 2014 i.e. in 40years. It was found that the capacity was reduced to 552.64Mm^3 from 523.928Mm^3 showing 5.20 % of loss in capacity of the total gross storage in 40 years. The rate of sedimentation was estimated as 0.718Mm^{3}year^{-1}.

***Key Words*: *Normalized Difference Water Index (NDWI), Prizmoidal formula, Sedimentation, Impoundment, Linear interpolation/ extrapolation technique*.**

1. INTRODUCTION

Though more than two thirds of the earth's surfaces are enclosed by water, less than 3 % of that is fresh water available. A huge extent of fresh water is unfeasible as it is trapped in different forms such as polar ice, ice caps and in the atmosphere. Therefore, roughly 0.003 % of the world's water is available for human consumption. Due to the rapid population growth and development of the world in the last century, the demand for water has greater than before. As a result, most of the rivers have been misused and a few rivers are still flowing in their natural form. Soil and water are the vital resources in the watershed that have to be managed suitably for continued supply of ecosystem service area such as proper water quality and quantity, to support a widespread and diverse range of utilization. Most of the problems in water resources sector like scarcity of water, inadequate storage and sedimentation in water bodies which are common in. arid and semi-arid regions of the world.

Soil particles originating from erosion processes in the catchment are propagated along with the river flow process and occur in a stream, ravine (nalas) and in the river basin system. The sediment brought by the stream into the reservoir starts settling down and gets deposited on the bed of the reservoir at all levels. The coarser particles settle first. The finer particles are carried in suspension and may finally settle down on the reservoir floor while some of these are passed over the spillway or through the outlets to the downstream of a dam. If the concentration is high, density current occur along the floor of the reservoir. At higher reservoir levels finer particle initially get deposited in the live storage space but successively move into the dead storage space depending on inflows due to successive floods, the drawdown of the reservoir and operation of outlets. Thus the deposit of sediment can affect the storage volume available at all levels. Loss of storage space is estimated at the planning stage and provisions are so made that the benefits of the reservoir are not adversely affected. Sedimentation in reservoirs occurs not only in dead storage, but also in the live storage region simultaneously, which reduces the useful storage and affects the water utilization pattern of the water resources project. Hence the critical assessment of each of the major and medium reservoirs became necessary, so that to ascertain the current reservoir live storage capacity for efficient and productive management of water resources and if any catchment area treatment needed can be applied in time. Some conventional methods are used for estimation of sediment deposited in a reservoir, such as hydrographic survey and inflow-outflow approaches, but these methods are clumsy, time consuming and costly. There is a need for developing and conveying simple methods, which require less time and are cost-effective.

In the present study the objective is to estimate the present storage capacity of Kabini Reservoir and capacity loss due to sedimentation/Siltation, through Satellite Remote Sensing.

1.1 Necessity

The well-organized use and management of available water in the reservoirs is the demand of time. Day by day raising population and uncertainty of climatic changes, creating pressure on available water resources. The analysis of sedimentation data of Indian reservoirs shows that the annual siltation rate has been generally 1.5 to 3 times more than the designed rate and the reservoirs are generally losing capacity at the rate of 0.30 to 0.92 percent annually. The consequence of loss in storage due to sedimentation is precluding the intended usages such as flood protection/ moderation, irrigation, hydro-power generation, etc.

2. DESCRIPTION OF THE STUDY AREA

The study area chosen for this study is Kabini Reservoir. The reservoir has been classified as hilly according to the Indian Standard Code no. 5477.The dam was built in the year 1974. It is masonry, gravity dam with overflow and non-overflow sections with earthen flanks on either side. The exact location of the dam is near Beechanahally villages in H.D.Kote Taluk, Mysuru District, Latitude $11^0$56'27" N, Longitude 76^0 20' 17" E. The catchment area at the dam site is 2142 Km^2, the overall length of the dam is 2733m and the area of the water spread at FRL is 61 Km^2. The live storage of the reservoir is 15.66 TMC and an original gross storage of 19.52 TMC. The shape of the reservoir is almost elongated. Its longest periphery from the axis is about 80 km. The average annual rainfall in the catchment up to Kabini is 1788 mm. About 80.90% of the annual total rainfall occur during the monsoon season (Jun-Sept). The average annual inflow at the dam site is 7197×10^6 m^3. The basin represents an uneven landscape with a combination of hills and valleys. The eastern and western margins of the basin have hilly range stranding NS. The central part is a plain with minor undulations. Overall slope of the basin is towards south.

Figure -1: Index plan of the Kabini catchment.

3. Material and Methods

To predict the Sedimentation from the reservoir, it is necessary to have the records of annual maximum and minimum observed variation in water levels 2013-14 covering most of the live storage zone i.e. from RL 2266 ft to FRL 2284ft .Also Impound Area–elevation–storage relationship for the reservoir with details of and daily water level data for the period from 2013-14 were collected from dam authorities. For the assessment of the sediment deposited in the reservoir, the satellite data were used to extract basic information, i.e. the water spread area at particular water surface elevations. The several dates of the satellite data used and the respective water level during the pass of the satellite over the reservoir are given in Table 1. It is generally preferable to carry out remote sensing based reservoir sedimentation study from the highest to lowest reservoir level chronologically. It was observed that there were very few imageries for one single water year during which there was a maximum fluctuation in reservoir water levels

Table -1: Browsed data for cloud free imageries pass for Kabini Reservoir

Sl. No	Path	Row	Satellite	Capture date	Water Level
1	145	52	LANDSAT_8 OLI_TIRS	16-Dec-13	690.37
3	145	52	LANDSAT_8	01-Jan-14	691.93
5	144	52	LANDSAT_8	11-Feb-14	693.20
6	144	52	LANDSAT_8	31-Mar-14	693.50
7	144	52	LANDSAT_8	2-May-14	693.68

The basic idea of Satellite Remote Sensing method for evaluation of reservoir sedimentation is to find out the water spread area of the reservoir from satellite data for various water levels between MDDL (Minimum Draw down Level) and FRL (Full Reservoir Level). The fact that the water spread area of reservoir at various elevations keeps on reducing due to sedimentation. This water spread areas of the reservoir at various levels between FRL and MDDL in different months of the year could be assessed from satellite imageries. Knowing the reservoir levels as ground truth on date of pass of the satellite, Elevation-Capacity curves could be established and compared with that at the time of impoundment of the reservoir. Any shift in the capacity curve will specify the extent of loss of reservoir capacity. The reservoir capacity between two successive levels is assessed using the

Prizmoidal formula and a revised elevation capacity can be generated.

The Flow chart showing methodology in brief for estimation of the capacity of reservoir sedimentation survey using remote sensing technique is given below,

Figure -2: Conceptual framework Reservoir sedimentation analysis

Though spectral signatures of water are quite distinct from other land features like vegetation, built-up area, soil surface, and man-made developments, however identification of water pixels at the water/ land interface is a bit difficult and depends on the interpretation ability of the analyst. Deep-water bodies have quite distinct and clear representation in- the imagery compared to shallow water. But very shallow water can be misguided for soil while saturated soil can be misguided for water pixels, especially along the boundary of the reservoir. Secondly, it is also likely that a pixel at the soil/water interface will stand for mixed conditions. Therefore, the methodologies commonly used in digital image processing technique include: thresholding, vector generation and modeling of water-land boundary delineation was required besides visual interpretation. The condition is applied in the form of a model in the ERDAS IMAGINES software and the model is run.

This technique is used here for identification of water pixels, which can be defined as:

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

The normalized difference water index (NDWI) is a new method that has been adopted to delineate open water features and strengthen their presence in remotely-sensed digital imagery. The NDWI makes use of reflected near-infrared radiation and visible green light to strengthen the presence of such features while expelling the presence of soil and terrestrial vegetation features.

The reservoir capacity between two elevations was computed by prizmoidal formula using water spread areas obtained above:

$$\Delta V_{1-2}= \Delta h(A_1+A_2+\sqrt{A_1A_2})/3$$

Where, ΔV_{1-2} = Volume between elevation E_2 and E_1 ($E_2>E_1$)

$\Delta h = E_2-E_1$

A_1, A_2 = Water spread areas at elevation E_1 and E_2

The overall reduction in capacity between the lowest and the highest observed water levels can be obtained by adding the reduced capacity at all levels. It is important to mention here that the volume of sediments deposited below the lowest observed level cannot be determined using remote sensing data. Therefore, the volume of reservoir below the lowest followed level is assumed to be the same before and after the sedimentation. Because of this reason, it is not possible to estimate the actual sedimentation rate in the whole of the reservoir. It is only possible to evaluate the sedimentation rate within the particular zone of the reservoir.

4. RESULTS

The areas of islands present in the reservoir were deducted from the total water spread area from imageries. Isolated water pixels surrounding the water spread area were not found, however, some water pixel seen near the boundary of reservoir, which have shown no hydraulic connectivity were removed. Similarly, water pixels in the downstream of the reservoir were not a part of the reservoir area, hence were removed.

The cumulative revised capacity of the reservoir at the observed lowest level (690.37m) was assumed to be the same as the original cumulative capacity (266.88Mm^3) at this elevation. Above the lowest observed level, the cumulative capacities between the consecutive levels were added up to arrive at the cumulative original and revised capacities at the maximum observed level. Calculation of sediment deposition in Kabini reservoir is given in Table 2 after calculating the total water spread area of the reservoir. The difference between the original and estimated cumulative capacity represents the loss of capacity due to sedimentation in the live zone of the reservoir.

Following Table 2 gives the status of loss in live storage of the reservoir during the above survey along with loss in capacity, annual rate of siltation as a percentage loss in the capacity since 1974 to the latest survey by SRS technique in 2013-14.

Table -2: Kabini reservoir capacity loss estimation due to sedimentation

Date	Elevation (m)	As per PIS 1974 (sq.km)	As per RS2013 (sq.km)	Depth (m)	Volume As per PIS 1974	Volume As per RS2013
2-May-14	690.37	41.06	39.20			
31-Mar-14	691.93	45.15	44.36	1.56	67.21398	65.135337
16-Dec-13	693.20	50.08	48.66	1.27	60.444	59.046652
1-Jan-14	693.50	50.46	49.30	0.30	15.08231	14.693895
11-Feb-14	693.68	50.69	50.34	0.18	9.104266	8.9674372

Date	Elevation (m)	Volume As per RS2013	Loss of volume	Cumulative capacity 1974 (M.cum)	Cumulative capacity RS 2013-14 (M.cum)
2-May-14	690.37			266.880	266.880
31-Mar-14	691.93	65.135337	2.0786433	334.094	332.015
16-Dec-13	693.20	59.046652	1.3973458	394.538	391.062
1-Jan-14	693.50	14.693895	0.3884184	409.620	405.756
11-Feb-14	693.68	8.9674372	0.1368291	418.725	414.723

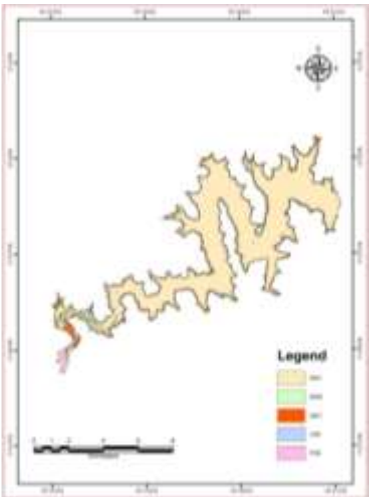

Figure -3: Superimposed Water Spread Areas of Kabini Reservoir.

The cloud free satellite data at F.S.L., i.e. 696.163m was not available. To estimate revised capacity on this level, a scattered graph has been plotted between reservoir elevations and revised Cumulative capacity. A best fit curve has been plotted with a coefficient of regression 0.99. The equation of the best fit curve has been used to estimate revised capacity in 696.163m and computed as 523.928Mm³.The results show that the volume of sediment deposited during 1974 to 2013-14 (40 years) between the maximum and minimum observed levels (685m and 696.16m) is 28.71 Mm³. If the uniform rate of sedimentation is assumed, then as per the 2013-2014 analysis, the sedimentation rate in the zone is 0.718 Mm³ per year.

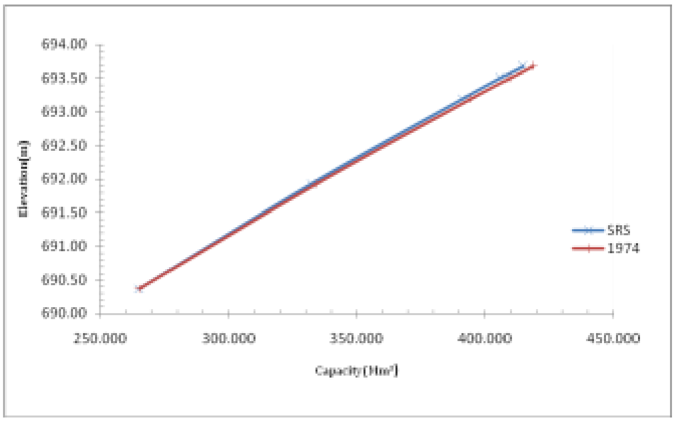

Figure -4: Graph showing loss in gross capacity of Kabini Reservoir

The plot of original and estimated cumulative capacity as derived using remote sensing technique is shown in Fig-4 for the year 1974-2014.

Table -3: Loss of storage in the Reservoir

Sl. No.	Year of Survey	Period (Years)	Reservoir Capacity (M.cum)	Loss of Capacity (M.cum)	% cumulative	Observed rate of siltation
1	1974		552.64			
2	2014	40	523.92	28.711	5.20	0.718

The following are the summary of the results:

a) The gross, dead and live storage capacities of Kabini reservoir for the year 1974 were 552.642 Mm³, 168.838 Mm³ and 274.789 Mm³ respectively.

b) The overall loss in capacity of the Kabini reservoir since its impoundment in 1974 to remote sensing survey of 2014 comes out to 28.711 Mm³, which is 5.20% of the gross storage.

c) The reservoir storage capacity at FRL was found to be of 552.64 Mm³ at the time when it first functioned, this capacity was reduced to 523.928 Mm³ i.e. by 5.20 % storage has been lost due to sedimentation in 40 years. Based on the Satellite Remote Sensing survey the annual sedimentation rate is 0.718 Mm³ year^{-1}

d) Thus, the average annual rate of loss of capacity is 0.13%, which appears to be comparatively on the lower side in comparison to the gross percent annual loss of 0.3 to 0.92% in many of the Indian reservoirs.

5. CONCLUSIONS

Using satellite imageries attempt a time and cost effective alternative for monitoring purpose. Moreover, a remote sensing technique, offered data acquired over a long time period and broad spectral range, are preferable to conventional methods. Satellite remote sensing technique highly cost efficient, easy to use and it depends upon lesser data and requires less time in analysis as compared to other methods. More exact data about the water spread area of the reservoir on a given date could be collected rapidly, which is basically difficult even with high-tech survey systems.

The major constraint of the remote sensing-based methodology is that the revised capacity below the lowest observed and above the highest observed reservoir water levels cannot be estimated. It is only possible to calculate the sedimentation rate within the zone of fluctuation of reservoir water level. From the point of view of the operation of the reservoir, this drawback is not very significant.

Since the reservoir level rarely falls below the minimum drawdown level in normal years, the interest mainly lies in knowing the revised capacity and the sediment deposition pattern within the live storage zone. However, if the sedimentation in the entire reservoir is to be found, in addition to remote sensing data analysis, the hydrographic survey within the water-spread area corresponding to the lowest observed elevation may be carried out. This will decrease the amount of effort required to carry out the hydrographic survey.

Further, it may be seen that the estimation of sedimentation by remote sensing is highly sensitive to the accuracy of: (i) Delineating the Land and Water Pixels, (ii) calculating water-spread area, (iii) reservoir water level information, and (iv) the original elevation-area-capacity data. Though, if the water level information is exact and the water-spread area is interpreted precisely, it is possible to determine the revised elevation-area-capacity curves quite precisely. Accuracy in ascertaining water pixels, mainly at the tail end of a reservoir, affects the accuracy of sedimentation assessment using remote sensing.

SRS survey could be done for the available imageries of the live storage zone only which covers only 49.75% part of Gross storage while 50.25% part remained not assessed. Thus giving sedimentation rate for whole storage on the basis of analysis of 49.75 % volume will not be appropriate, Therefore It would be appropriate if hydrographic surveys are conducted at longer intervals and the remote sensing based sedimentation surveys are carried out at shorter intervals, so as to give more accurate sedimentation deposition volume and rate with an integrated system.

The revised capacity of the reservoir is then compared with the original capacity of the year 1974 so as to give the loss in capacity from 1974 to 2014 i.e. in 40years. It was found that the capacity was reduced to 552.64Mm^3 from 523.928Mm^3 showing 5.20 % of loss in capacity of the total gross storage in 40 years. The rate of sedimentation was estimated as 0.718Mm^{3}year^{-1} considering total catchments of 2142 km^2.

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