RESERVOIR SEDIMENTATION STUDIES USING SATELLITE REMOTE SENSING TECHNIQUE AND MATHEMATICAL MODELING

MR. R. M. MANE
ME Scholar, Department of Civil Engineering STBCOE, Tuljapur, Maharashtra, India

PROF. P.A. HANGERGEKAR
HOD, Department of Civil Engineering STBCOE, Tuljapur, Maharashtra, India

ABSTRACT

Sedimentation in the reservoir gradually reduces its storage capacity. By keeping a check on the sedimentation and by providing control measures for the same, the reservoir life can be maintained. Ujjani dam was constructed for irrigation, water supply and power generation schemes. It lies in Solapur district which is a drought prone area. This makes Ujjani a socially and economically significant project for the state. In the present study, reservoir sedimentation for Ujjani reservoir is assessed for monitoring purpose. Two techniques namely Satellite Remote Sensing Technique (SRST) and mathematical modeling using HEC RAS, were used in the study for estimating sedimentation.

The advent of new computer technologies has enabled engineers to resolve equations of sediment transports and hydraulic issues using computer simulations and modeling. Numerical modeling has not only decreased the calculation time by making use of rapidly increasing processing power, but also made it easier to test effects of different sets of input variables in an improved way. A mathematical model in HEC RAS software was generated for Ujjani Reservoir. This sediment model was run for Quasi Unsteady flow which gave sediment volume change profiles.

The volume of sedimentation found by both the methods is in good agreement with each other. They are also compared with the previous hydrographic surveys. Limitations of the study and its future scope are also discussed at the end of the study.

Keywords: *Sedimentation, Ujjani reservoir, Satellite Remote Sensing technique, Mathematical model*

DATA USED

Data collected of the Ujjani reservoir for both methodologies Satellite Remote Sensing Technique and one dimensional model HEC RAS is discussed in the chapter.

SATELLITE REMOTE SENSING TECHNIQUE

Since the study is for determining the sedimentation in the reservoir, only recent years' satellite imageries are required for the studies. Landsat images were available for the years 2013 and 2014. II cloud-free, haze-free images covering the whole time period of two years were downloaded from the website earthexplorer.usgs.gov. Ujjani reservoir was covered in single image of Landsat-8 of path 146 row 47.

Reservoir water levels and the area elevation capacity curve were collected from state authorities. Data was arranged as per water level variation of the reservoir between FRL, and MDDL, for analysis, as shown in Table 1

TABLE 1&2 Imageries Date and Corresponding Reservoir Levels A-E-C Tables for Ujjani Reservoir for the Year 1977

Ujjani reservoir was constructed in the year 1980 but impounded since 1977. The original Area- Elevation-Capacity (A-E-C) table is given in Table 2

Sr.No.	Date of Satellite Passing	Observed WL (m)
1	**Bed Level**	**458**
2	29-May-13	486.35
3	13-May-13	487.28
4	**MDDL**	**491.03**
5	13-Mar-14	494.09
6	25-Feb-14	494.28
7	09-Feb-14	495.2
8	08-Jan-14	496.01
9	07-Dec-13	496.69
10	21-Nov-13	496.74
11	02-Sep-13	496.81
12	20-Oct-13	496.82
13	05-Nov-13	496.83
14	**FRL**	**496.83**

Level (m)	Water Spread Area (M. Sq.m.)	Capacity (M. Cu.m.)
Bed level 458.00	0	0
485	110.2	898.636
485.6	116.502	966.638
486	120.8	1014.096
486.6	128.638	1088.913
487	134	1141.438
487.6	142.317	1224.321
488	148	1282.381
488.6	157.149	1373.912
489	163.4	1438.017
489.6	171.013	1538.792
490	177.229	1609.059
490.6	187.79	1719.568
M. D. D. L. 491.00	197	1796.886

491.6	208.295	1918.458
492	216	2003.313
492.6	227.894	2136.465
493	236	2229.239
493.6	250.967	2375.306
494	261.2	2477.738
494	276.416	2638.996
495	286.8	2751.633
495.6	301.793	2928.192
496	312	3050.944
496.6	329.618	3243.406
F. R. L. 496.83	336.5	3320.008

Landsat images are already georeferenced so toposheets were not required for geo-referencing the images. Hydrographic survey details are required for analyzing the rate of siltation and percent annual loss. These were available for the years 1991.1998 and 2001. The details are as shown in the Table 3

TABLE 3 Hydrographic Survey Data Details

Year	Reservoir capacity Mm^3	Loss of Capacity Mm^3		Period (years)		Rate of Siltation Mm^3/yr		% loss of capacity from 1977	% annual loss
		From 1977	From previous survey	From 1977	From previous survey	From 1977	Between two surveys		
1977	3320.008	0.000	0.000	0	0	0.000	0.000	0.000	0.000
1991	3032.526	287.482	287.482	14.000	14	20.534	20.534	8.659	0.619
1998	3005.206	314.209	27.420	21.000	7	14.995	3.917	9.485	0.452
2001	2972.827	347.181	32.279	24.000	3	14.466	10.760	10.457	0.436

MATHEMATICAL MODEL-HEC RAS

The reservoir portion and at least 10-15 kilometers river portion, just upstream of Reservoir, needs to be construct for a sediment HEC RAS model for effective erosion and sedimentation modeling. This requires a lot of data of the river. The Gauge-Discharge and Sediment data of a River data Gauging Station in the upstream of Ujjani Reservoir was requested to the State and Central Government Irrigation Departments. Phulgaon. Dound. Pargaon, Lonikand. Holkarpur were the stations nearby to study area. But full required data was not available for all the stations. The nearest station to the study area was Dound (47km from end of reservoir) but the sediment data for that station was not available. Lonikand and Holkarpur had only rainfall data. Phulgaon data was irrelevant as study requires upstream data, and the station is in the downstream of the Reservoir. So the study reach was extended 79.5km upstream of Reservoir's end, till the Pargaon station, as Gauge-Discharge data and Suspended Sediment data was available for that station.

As explained above, it is necessary in a sediment model, to extend the upstream boundary of the model for a few kilometres i. e. to include few cross sections of river portion, upstream of reservoir in the model. For this study, surveyed cross sections for this long reach of the river and reservoir were unavailable. So the toposheets covering the area of Ujjani reservoir and upstream Bhima river were used.

The details of Toposheets used are as follows:

i. 47 N/4, 47 J/15, 47 J/16, 47 J/10, 47 J/l1
ii. Scale : 1:50,000 with elevation contour interval of 20m
iii. Area's Latitude ranging between 18° 02' 42" N - 18° 22' 12" N and Longitude ranging between 74° 45' 00" E - 75° 12" 36" E.

Total 355 cross sections for a reach length of 177.5 km from the dam wall, were extracted from the toposheets and Google Earth:

i. Reservoir-196 nos. (98km)
ii. River-159 nos. (79.5km)

The interval between cross sections was taken as of half kilometer (500 metres)

Daily Discharge of the Pargaon station for the years 1987-2010 was referred for entry of the flow series. The generated flow hydrograph is shown in Figure 1

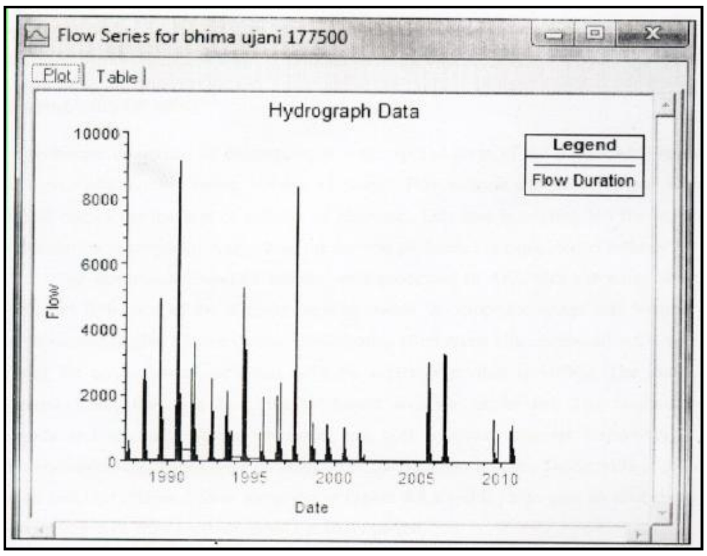


FIG. 1 Flow Hydrograph for Pargaon Station

Daily Suspended-load sediment data of Pargaon station from 1987-2010 was available. It was processed and used for generation of bed gradation samples.

Daily Reservoir levels were not available for preparation of Stage Series.

Out of all of the data required, some data was not available. Thus assumptions were made for those cases, which are explained in the presentation and analysis chapter.

PRESENTATION AND ANALYSIS OF DATA

This chapter involves a detailed explanation of processing of the collected data and analysis for the study. It also states the assumptions followed in the study for the unavailable data. The chapter concludes with the limitations of the two methods.

ANALYSIS OF SRST

The technique comprises of delineation of water spread areas of the downloaded imageries and converting it into present volume of water. This volume can be compared with the original one to get the loss of volume of reservoir. This loss is nothing but the volume of sedimentation in reservoir. Analysis of the method performed is explained as follows.

The downloaded satellite images were processed in ARC-CIS software. The third, fourth and fifth band of the imagery were uploaded. A composite image was formed. This was processed to give a False Colour Combination (Red green blue combination). It was then clipped for convenience, such that only the reservoir portion is visible. The image was digitized. Using the Area Tool, the catchment area was delineated. The catchment area expands and contracts during monsoon and post monsoon seasons respectively. Thus different catchment shapes were obtained from the different images. Thumbnails of the water spread areas on different dates are given in Figure 1 and 2 to give an idea about how the reservoir area changes throughout the study period.

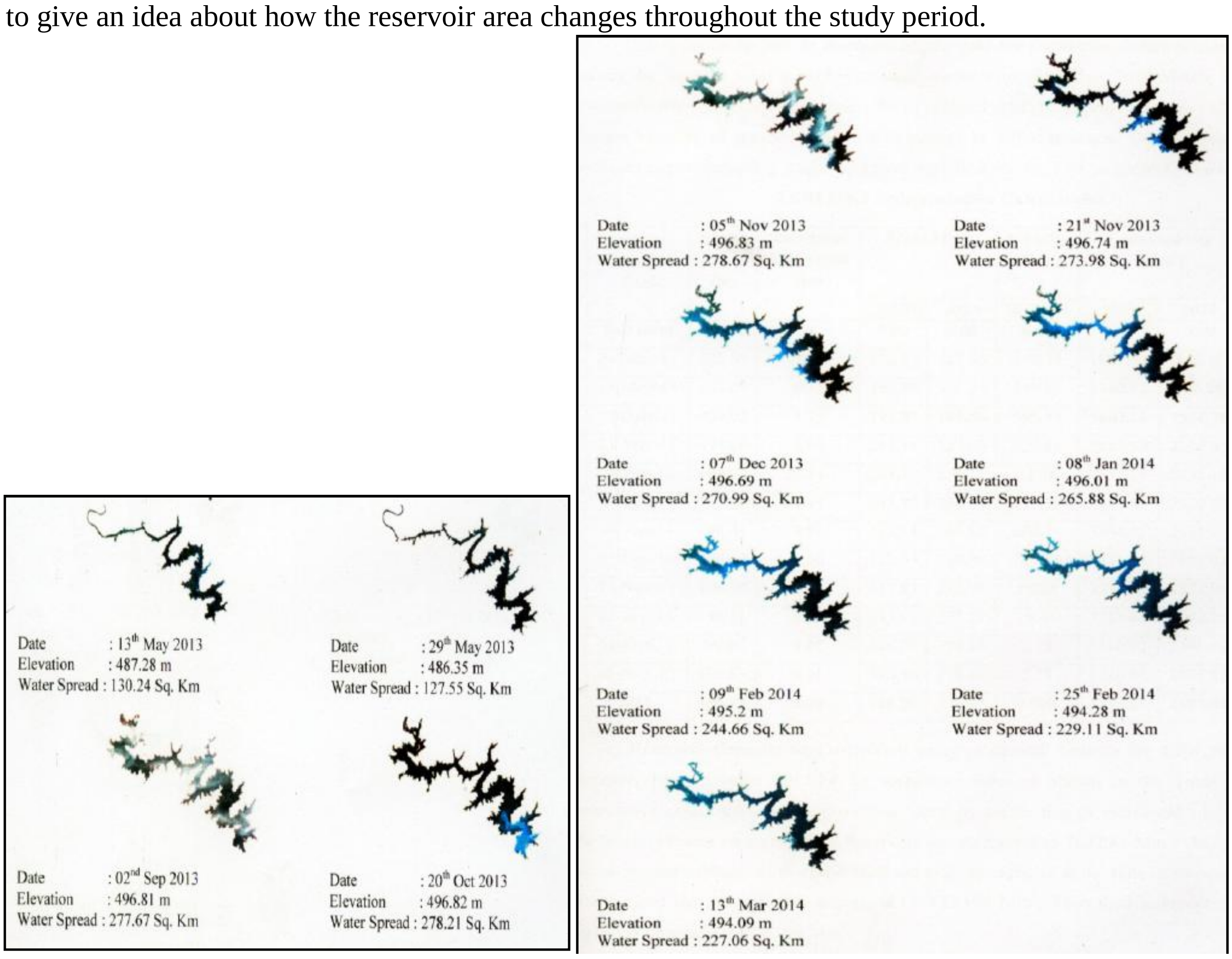


FIG 2 Water Spread Areas of the Imageries

For calculating loss In storage capacity and for estimating sedimentation, capacity survey by remote technique was carried out for May 2013-March 2014. The difference between cumulative capacities of original (1977) and present surveys (2014) gave present capacity of reservoir and loss in storage in different zones. Satellite image data is arranged as per increasing Reservoir Level from Bed level to FRL as presented in Table 4

TABLE 4 Sedimentation Calculations

Sr no	Date of Satellite Pass	Water Level (m)	Elevation Difference (m)	Area (Mm^2)		capacity (Mm^3)	Cum capacity (Mm^3)		loss in capacity (Mm^3)
				1977	2014	RS2014	1977	2014	RS2014
1	**Bed level**	**458.00**	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
2	29-May-l3	486.35	28.35	125.37	127.55	876.39	1057.74	876.39	181.35
3	13-May-13	487.28	0.93	137.88	130.24	119.87	1180.12	996.26	183.86
4	**MDDL**	**491.03**	**3.75**	**197.57**	**183.56**	**585.52**	**1803.13**	**1581.78**	**221.35**
5	13-Mar-14	494.09	3.06	263.44	227.06	627.06	2501.85	2208.85	293.00
6	25-Feb-14	494.28	0.19	268.30	229.11	43.34	2552.99	2252.18	300.81
7	09-Keb-14	495.20	0.92	291.80	244.66	217.90	2810.49	2470.08	340.41
8	08-Jan-14	496.01	0.81	312.54	265.88	206.71	3054.52	2676.79	377.73
9	07-Dec-13	496.69	0.68	332.34	270.99	182.53	3274.01	2859.32	414.69
10	21-Nov-13	496.74	0.05	333.83	273.98	13.62	3290.44	2872.94	417.49
11	02-Sep-13	496.81	0.07	335.91	277.67	19.31	3313.44	2892.25	421.19
12	20-Oct-13	496.82	0.01	336.20	278.21	2.78	3316.72	2895.03	421.69
13	05-Nov-13	496.83	0.01	336.50	278.67	2,78	3320.01	2897.81	422.19
14	**FRL**	**496.83**	**0.00**	**336.50**	**278.67**	**0.000**	**3320.01**	**2897.81**	**422.196**

Reservoir Capacity was calculated using, prismoidal formula for different levels of reservoir for the years 2013-14 for respective dates as shown in the Table 1 Then cumulative capacity of the reservoir was found by summation of individual zones between the levels. Present capacity of the Reservoir was estimated as 2897.81 Mnr^1. On comparison of the present capacity of reservoir with the original capacity at the time of impoundment, it was noticed that the capacity decreased by 422.196 Mm^3. Thus total sedimentation in the reservoir upto date is 422.196 Mm^3.

Data from previous reservoir capacity surveys done for the year 1991, 1998 and 2001, was compiled. Rate of siltation and percent annual loss in reservoir capacity were estimated as presented in Table 5 From Table 5 showing loss of gross storage it was observed that there was a loss in capacity of 287.482 Mm^3, 314.902 Mm^3, 347.181 Mm^3 and 422.194 Mm^3 during 1977 to 1991 (14 years), 1998 (21 years), 2001 (24 years), and 2014 (37 years) respectively. The rate of siltation was 20.534 Mm^3 / year up to 1991 and it decreased to 11.411 Mm^3 / year upto 2014. Reviewing the analysis of satellite imageries for Ujjani reservoir indicated that during the year 2014 the reservoir capacity was 2897.814 Mm^3. Percentage annual loss of capacity varied from 0.619% upto 1991 to 0.344% till 2014. This shows considerable decrease in the percent annual loss.

TABLE 5 Rates of Siltation and Percent Annual Loss

Year	Reservoir capacity Mm^3	Loss of Capacity Mm^3		Period (years)		Rate of Siltation Mm^3/yr		% loss of capacity from 1977	% annual loss
		From 1977	From previous survey	From 1977	From previous survey	From 1977	Between two surveys		
1977	3320.008	0.000	0.000	0	0	0.000	0.000	0.000	0.000
1991	3032.526	287.482	287.482	14.000	14	20534	20.534	8.659	0.619
1998	3005.106	314.902	27.420	21.000	7	14.995	3.917	9.485	0.452
2001	2972.827	347.181	32.279	24.000	3	14.446	10.760	10.457	0.436
2014	2897.814	422.194	75.012	37.000	13	11.411	5.770	12.717	0.344

LIMITATIONS OF SRS TECHNIQUES

i. Does not show changes in dead storage
ii. Specialized manpower required
iii. Accuracy depends on resolution of the image
iv. Special care required at land water interface to distinguish water pixels from land / soil. Accuracy of method will depend on this.
v. SRS techniques can give accurate estimates for shallow fan shape reservoirs and less for deep leaf shaped reservoirs (CWPRS Report no. 4626. 2009)

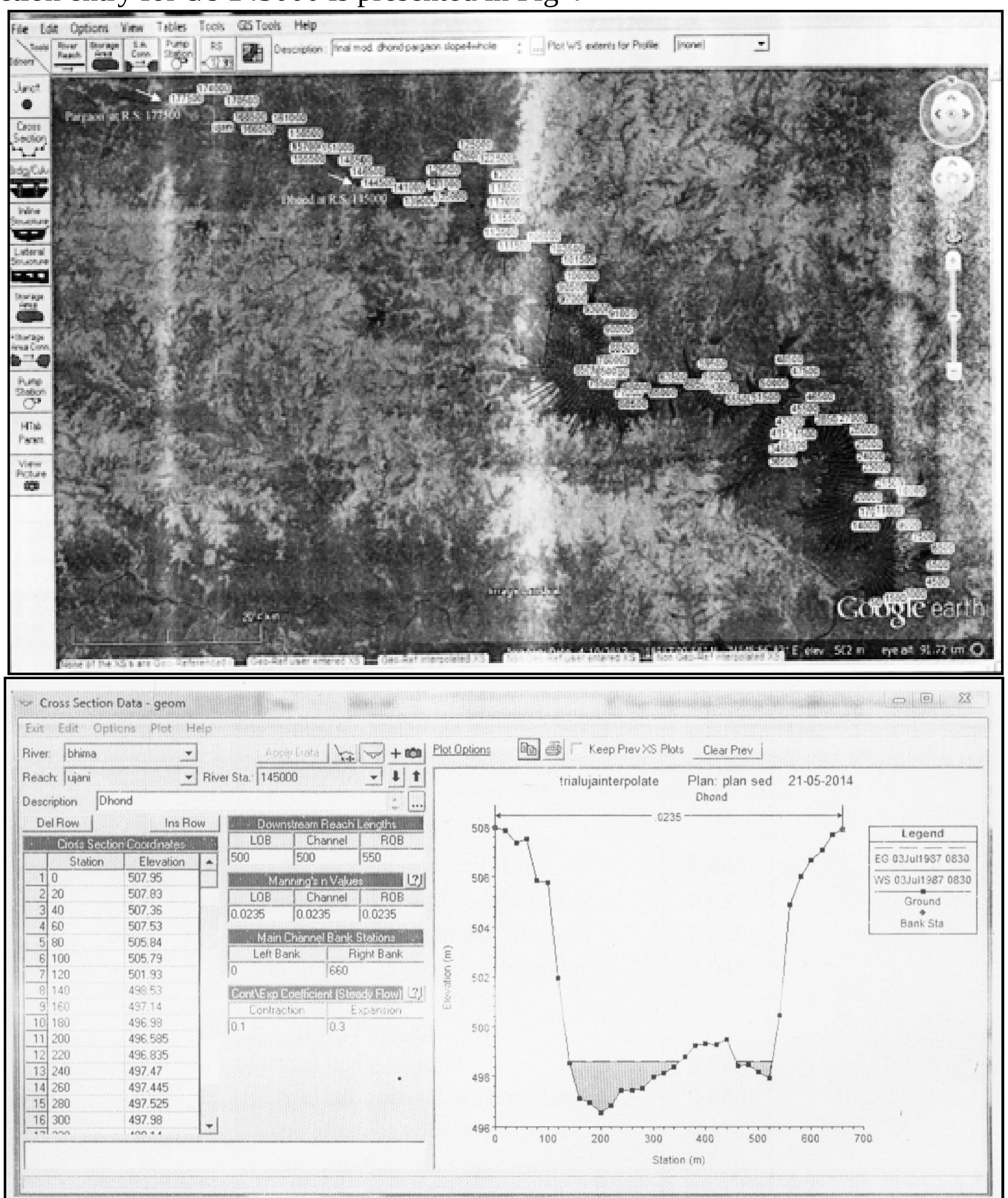
ANALYSIS OF MATHEMATICAL MODEL

The main entries for HEC RAS sediment transport model are Geometric Data (Topography creation). Quasi - Unsteady Flow Data (Flow series. Stage series), and Sediment Data (Sediment gradation curves and Sediment Transport Parameters) the model gives sediment volume change in the reservoir for the simulated period. The procedure followed for mathematical modeling is explained as follows.
Fig 4 presents the developed study reach. The meandering River - Reservoir reach was drawn as shown in the Fig 4

and consequently cross section entry was done.

Station-elevation data of each cross .section was fed along with the downstream reach length between this cross section and the immediate downstream cross section. Manning's n value was finalized considering the topography of the study area and was fed to the model. The Banks of the individual cross sections were also entered. The contraction and expansion coefficient were given as 0.1 and 0.3 respectively.

A sample cross section entry for c/s 145000 is presented in Fig 4



VALIDATION OK MODEL

In Validation of the model, the model is set to such topographic conditions that it behaves like the prototype. In this study, steady state condition was used for validation. The model was run for maximum and minimum discharges and stage at intermediate station Dhond was observed. For calibrating the model, the Manning's n table (Ven Te Chow 1959) was used as shown in Table 5 After calibrating the model; the simulated stage and observed stage at the station were compared. The results are displayed in the Table 5. Also the water surface profiles at the stations Pargaon and Dhond at chainage 177500 and 145000 are shown in the Fig. 5

TABLE 5 Typical Values of Manning’s Roughness Coefficient [28]

TYPE OF CHANNEL	*N*
Lined canals	
Cement Plaster	0.011
Untreated gunite	0.016
Wood, planed	0.012
Wood, unplaned	0.013
Concrete, troweled	0.012
Concrete, wood forms, unfinished	0.015
Rubble in cement	0.020
Asphalt, smooth	0.013
Asphalt, rough	0.016
Corrugated metal	0.024
Unlined canals	
Earth, straight and uniform	0.023

Earth, winding and weedy banks	0.035
Cut in rock, straight and uniform	0.030
Cut in rock, jagged and irregular	0.045
Natural Channel	
Gravel beds, straight	0.025
Gravel beds plus large boulders	0.040
Earth, straight with some grass	0.026
Earth, winding, no vegetation	0.030
Earth, winding, weedy banks	0.050
Earth, very weedy and overthrown	0.080

Manning's n was calibrated by trial and error method, for a range of values considered from the above table. The final values were taken as:

1) c/s 400-98000 (Reservoir) = 0.04
2) c/s 98500-118500 (River) = 0.022
3) c/s 119000-133000 (River) = 0.023
4) c/s 133500-177500 (River) = 0.0235

Different values were given for the river portion .and the reservoir portion as the grain size and the velocities, which are the main criterion for defining the manning's n, varied in both portions.

TABLE 6 Validation of Model

Discharge at Paragon (Cumees)	Simulated water level at Pargaon (metres)	Observed water levels at Pargaon (metres)	Simulated water levels at Dhond (metres)	Observed water levels at Dhond (metres)
8367	519.92	520	508.79	508.485
708.6	509.95	510.4	499.96	500.3

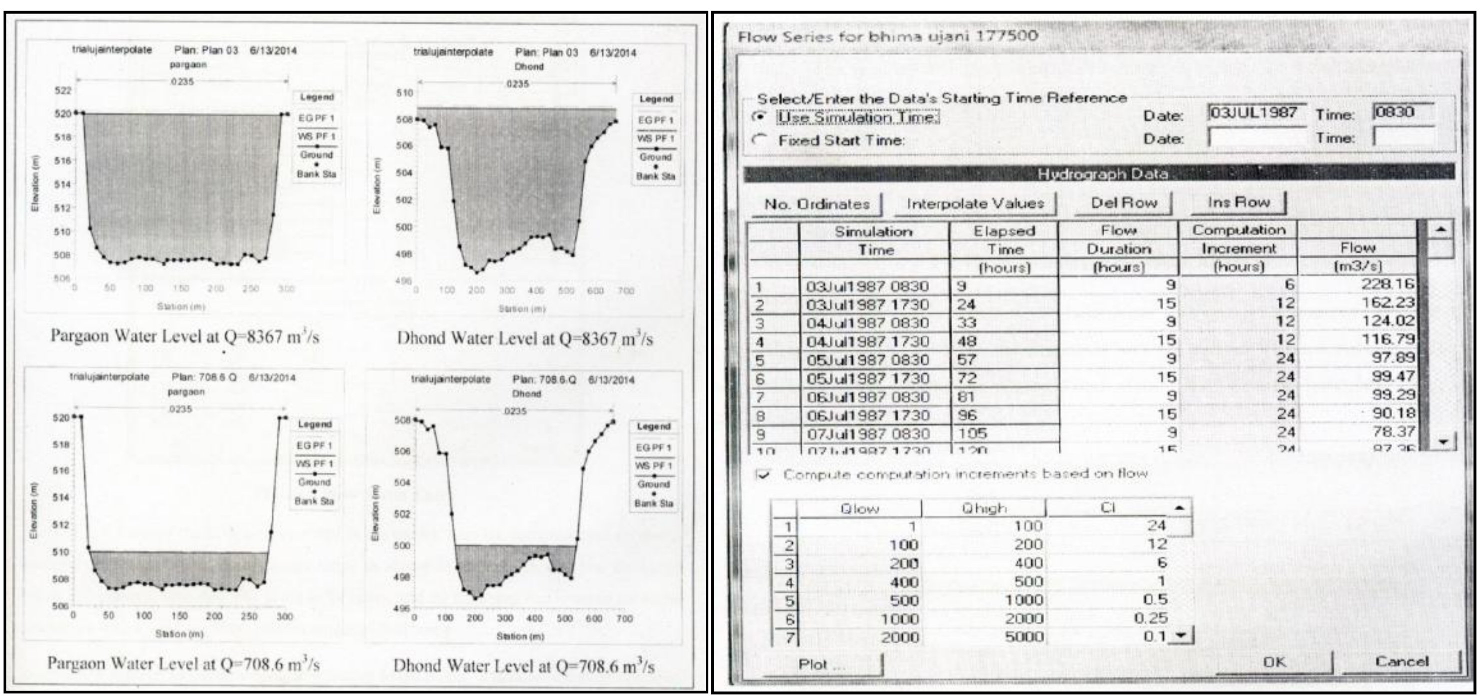


FIG. 6 Simulated Water Surface Level for Validation of Model & Flow Series Entry

The model was calibrated using above values of Manning’s n and results were obtained. The water levels- simulated and observed, at the stations were fairly comparable for further studies.

The Quasi-Unsteady Flow entry comprised of flow series on the upstream and stage series on the downstream. Paragon station Discharge data for the years 1987-2010 was used to form a flow series and was given as the upstream boundary in the model.

Fig 6 shows the flow series entered in the model. Also the computational increment was given to model based on discharge range as shown in the Fig 6 for low discharges below 100 cumecs, time step was given as 24 hours, and the time step was lowered for higher discharges with lowest for 5000-10000 cumecs as 0.01 hours.

Stage series is given as the downstream boundary to the model. It denotes the stages obtained in the reservoir for the particular discharges coming from the upstream boundary. So the stage data for the same dates and time as of the upstream boundary was fed to the model. The reservoir levels were kept varying between FRL to MDDL for Monsoon and Non Monsoon seasons for the downstream boundary. Fig 7 shows the stage series fed to the model.

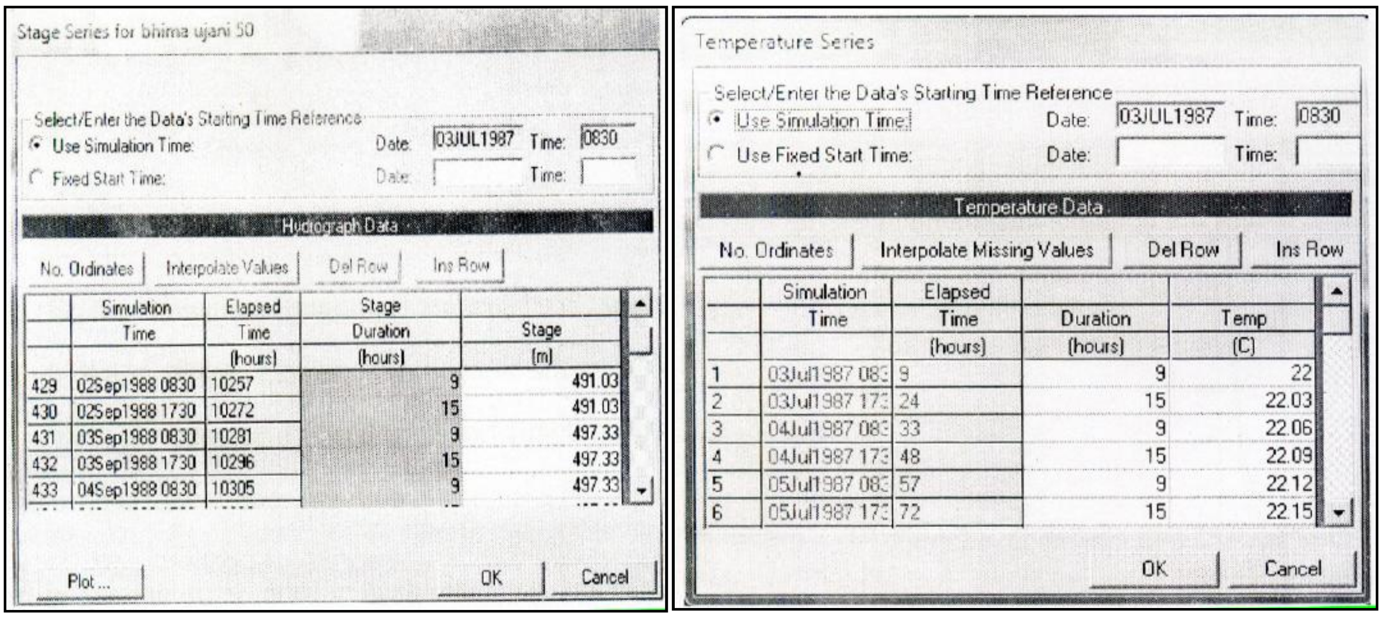


FIG. 7 & 8 Stage Series Entry Temperature Series Entry

Also a temperature series was entered because several aspects of sediment transport mechanics, particularly fall velocity, are sensitive to water temperature. Currently only one temperature per time step can be specified for the entire model. Fig 8 shows the temperature series fed to the model.

Suspended sediment data of Pargaon station was available for the years 1987-2010 from July-October, with a few years, 2003, 2004, 2007, 2008, 2011, 2012, and 2013 missing in between. The data is divided in the range of coarse, medium and fine sediment. As the range of sediment size was between 0.004mm to 128mm, the best suitable sediment transport parameters finalized were:

Transport Function : Laursen (Copeland)
Sorting Method : Exner 5
Fall Velocity Method: Van Rijn

The Laursen-Copeland (Eq 6) transport equation (Laursen, 1958) was selected to model this reach because of the dominance of very fine sand and coarse silt as well as the occurrence of gravel and cobbles. It is the only commonly used transport function that was developed over the coarse silt range and out performs other functions for non-cohesive fine materials.

The Minimum Elevation for the river portion was taken as 1m deeper than invert level. Minimum Elevation for the reservoir portion was taken same as invert level, assuming that there is no erosion in Reservoir. Only one entry is sufficient to the model; either Minimum Elevation maximum depth. This is to be selected based on site conditions.

Extents for erosion and deposition (Sediment banks) were assumed to be same as the cross section banks. Fig. 9 shows the sediment data fed to the model.

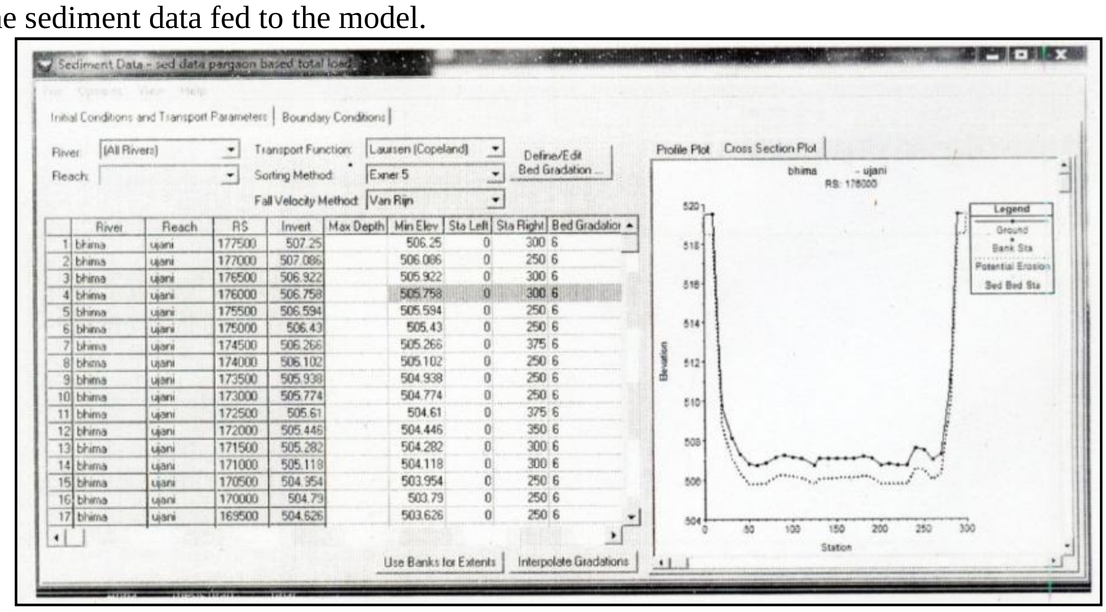


FIG. 9 Sediment Data Entry

Suspended-load sediment data of Pargaon station from 1987-2010 was used for generation of bed gradation samples. Bed load data of this station was not available. So bed load was assumed as 20% of suspended load and six samples were generated. These samples are shown in Fig 10

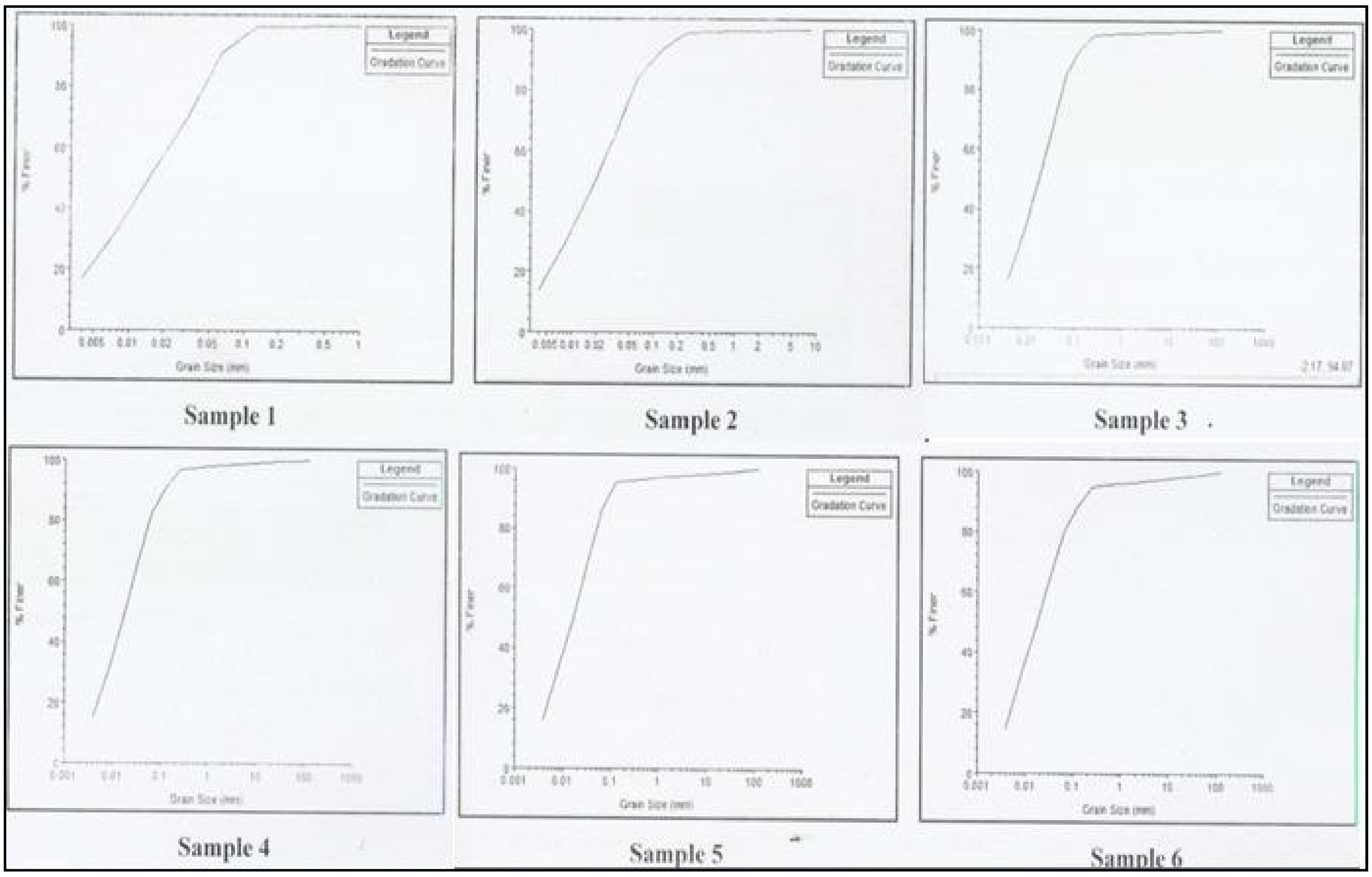


FIG. 10 Bed Gradation Curves

As total load data was not available for any of the station i.e. Paragon or Dhond for the study, the sediment upstream boundary condition was given as the equilibrium load as shown in Figure 11.

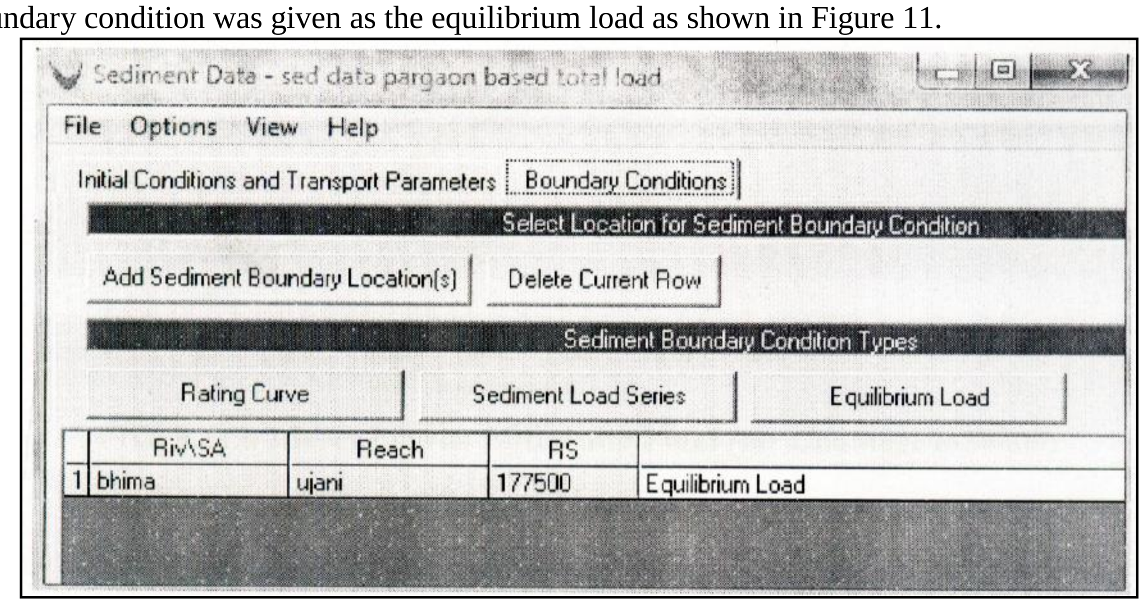


FIG. 11 Sediment Boundary Conditions

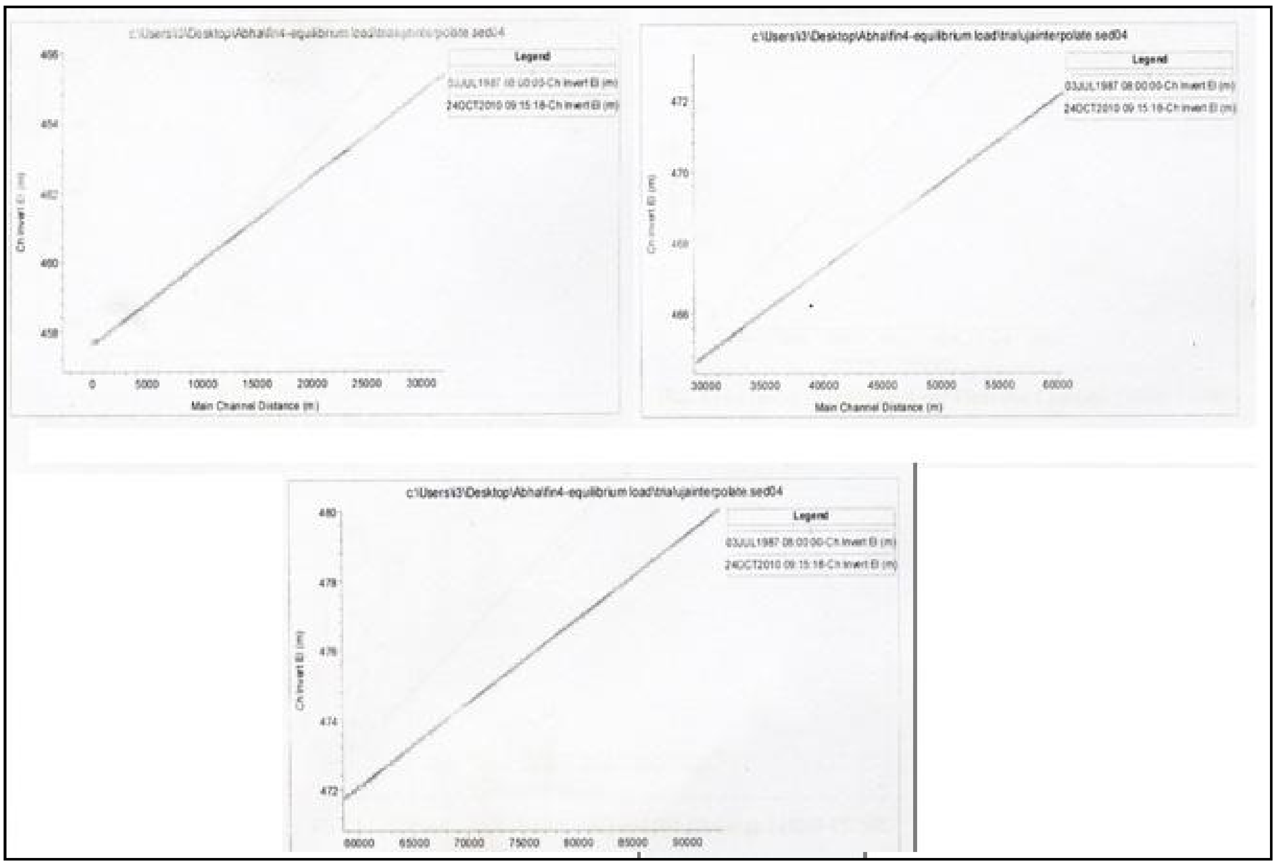
After all these entries, the model was run for Quasi Unsteady flow state. Output level 4 and final results were obtained.

OUTPUT OF 1-D HEC RAS MODEL

The model was run for the years 1987 to 2010. Following parameters were considered for the study.

1) Channel Invert levels - Initial and final
2) Cross Section changes
3) Velocity profile
4) Water surface profile
5) Net volume change over the cross section

The plots of each of the stated parameters were studied with respect to the L- Section of the Main Channel Distance (total reach chainage). Channel Invert level denotes the minimum bed level of the cross section. The initial channel invert levels for 03rd July 1987 and final channel invert level for 24(h Oct 2010 are shown in the Figures 11, 12,13,14,15,16and 17 of for respectively stated chainages. The final invert level above initial invert level and vice versa denotes sedimentation and erosion respectively, for that cross section.



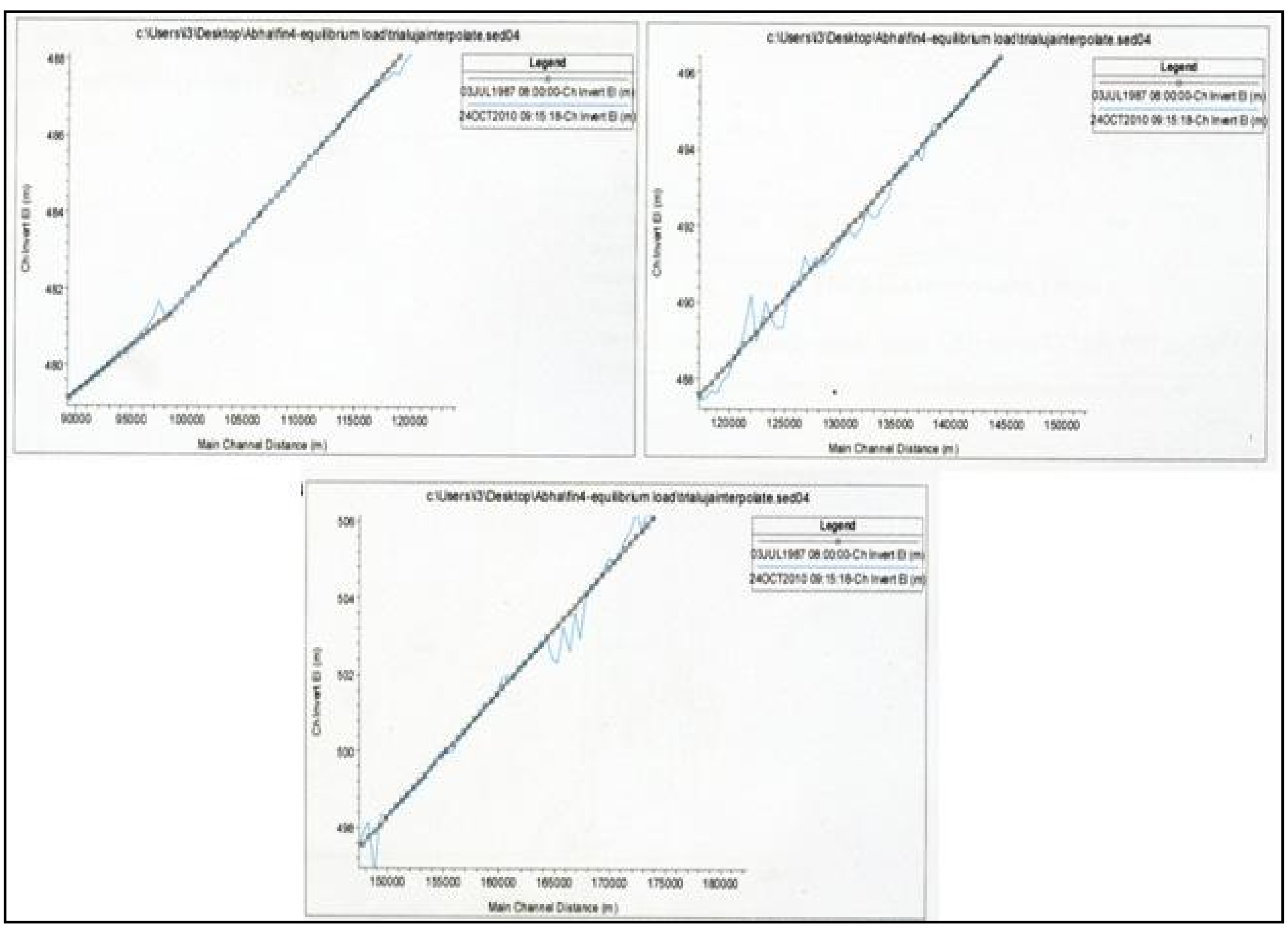


FIG. 12 Invert Levels-Initial and Final (for Chainage 60000-90000) FIG. 13 Invert Levels-Initial and Final (for Chainage 145000-177500)

Fig. 13 shows sample cross section changes in shape due to sedimentation at chainage 167000 for different flows in respective years.

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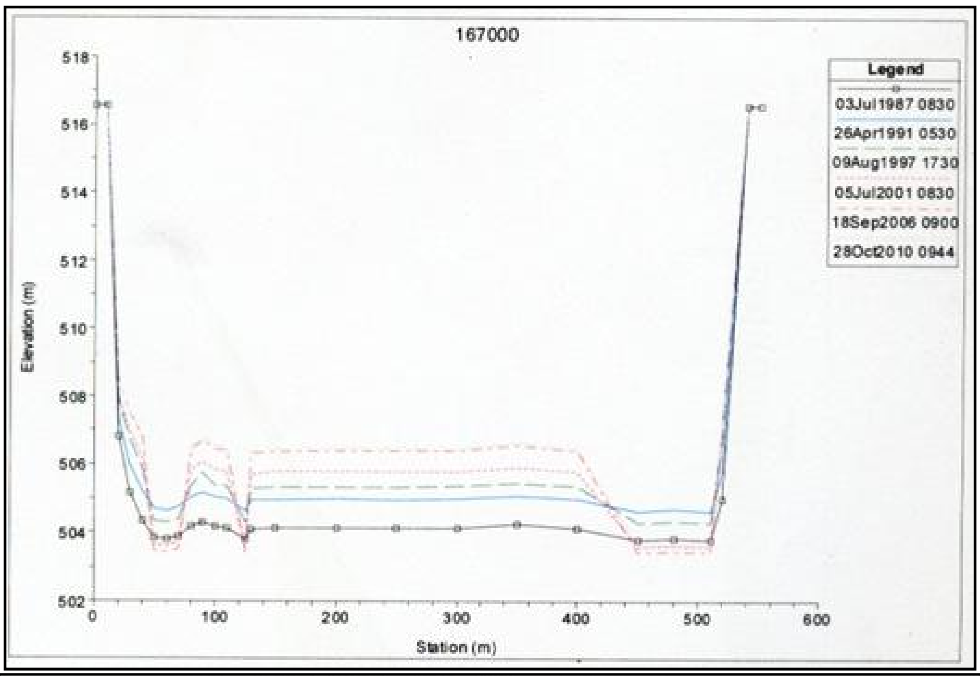


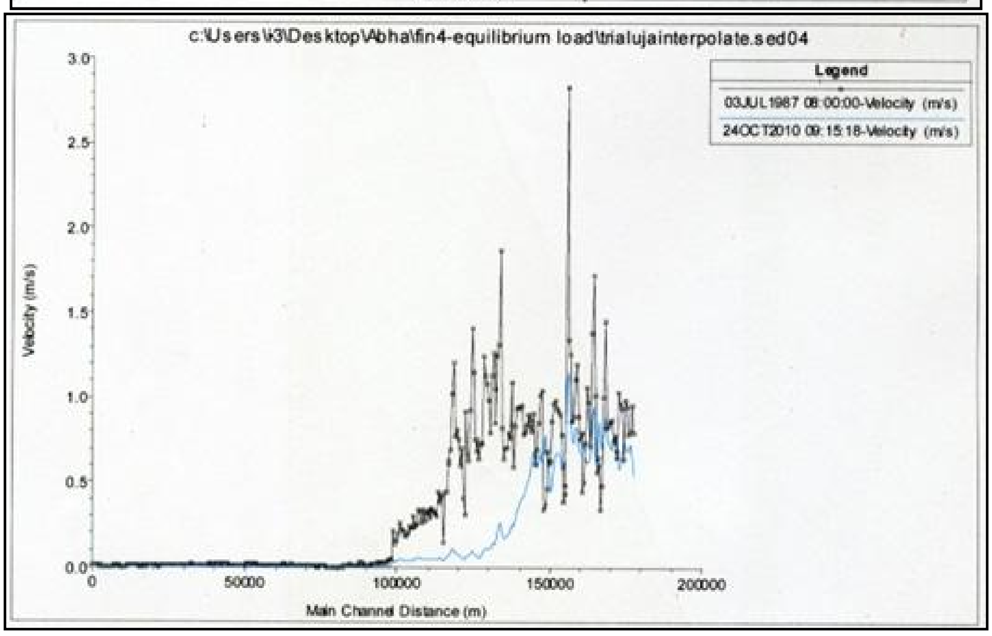


FIG. 14 Velocity Profile

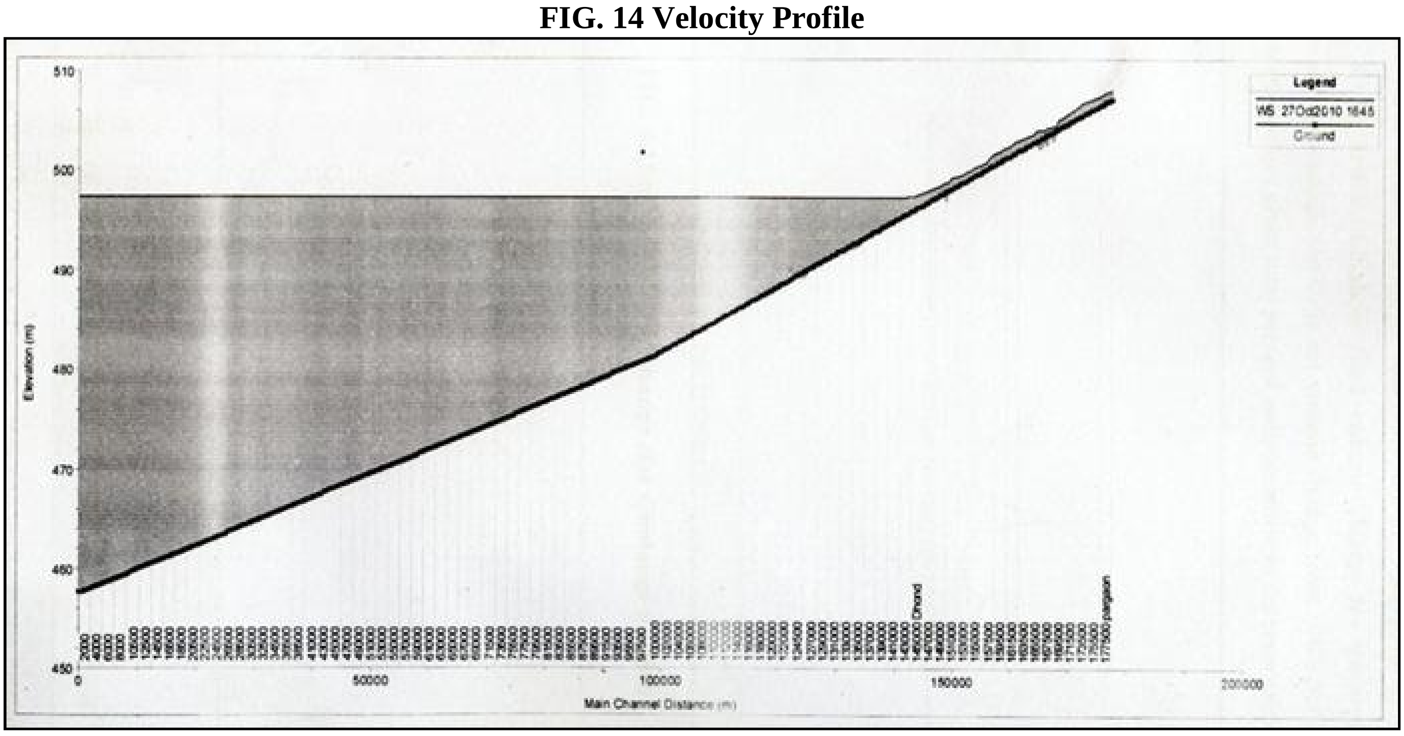


Fig. 15 shows water surface profile of full reach on 27th Oct 2010 above show final volume change for the respectively stated chainages. This volume change shown is net volume change from 1987-2010. Summation of these volume change values gives total present sedimentation in the reservoir in cubic metres.

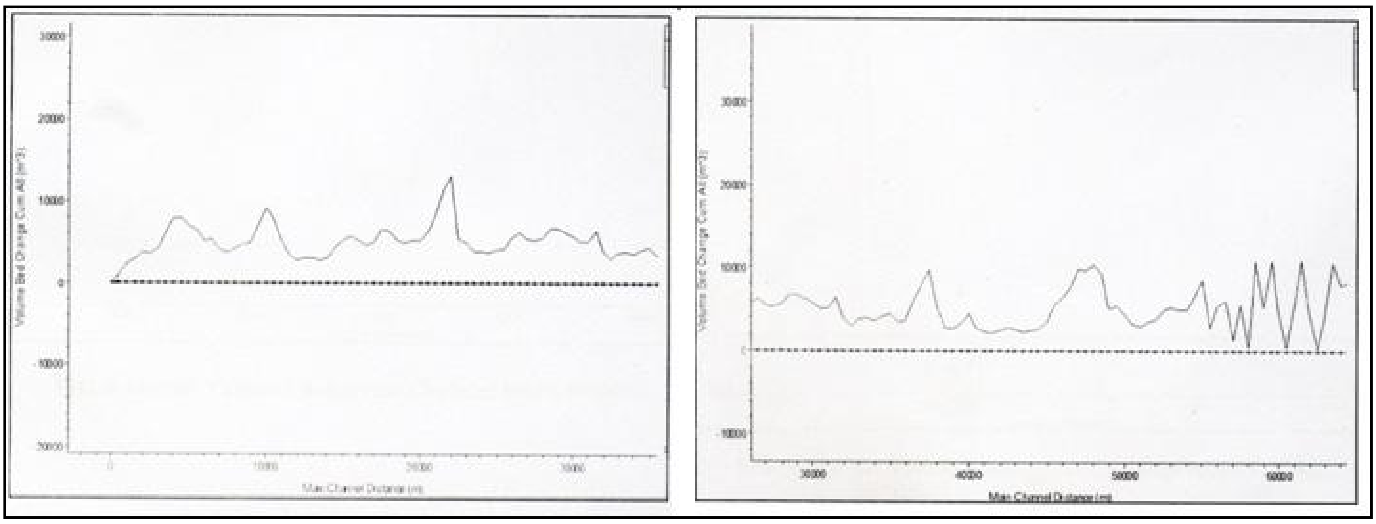
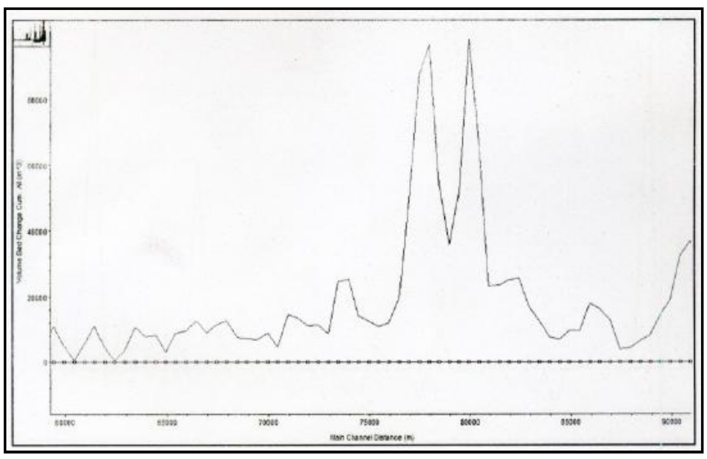


FIG. 16 Net Volume Change (for Chainage 30000-60000)



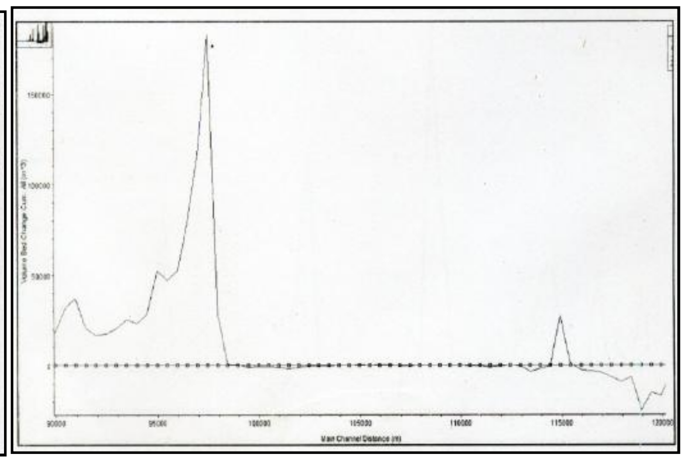
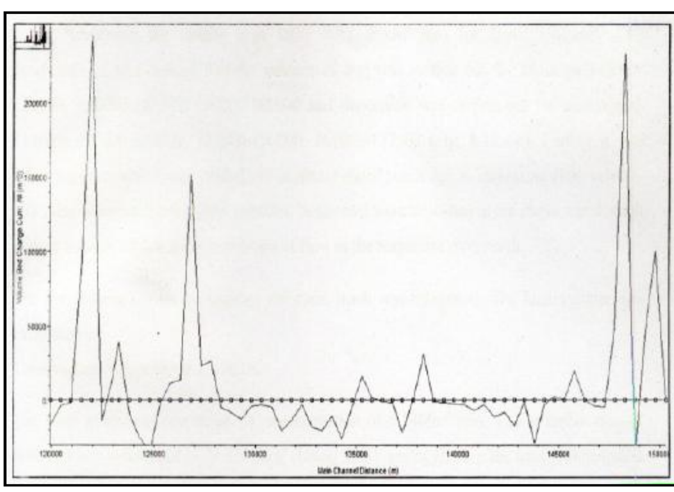


FIG. 17 Net Volume Change (for Chainage 60000-90000) FIG. 18 Net Volume Change (for Chainage 90000-120000)



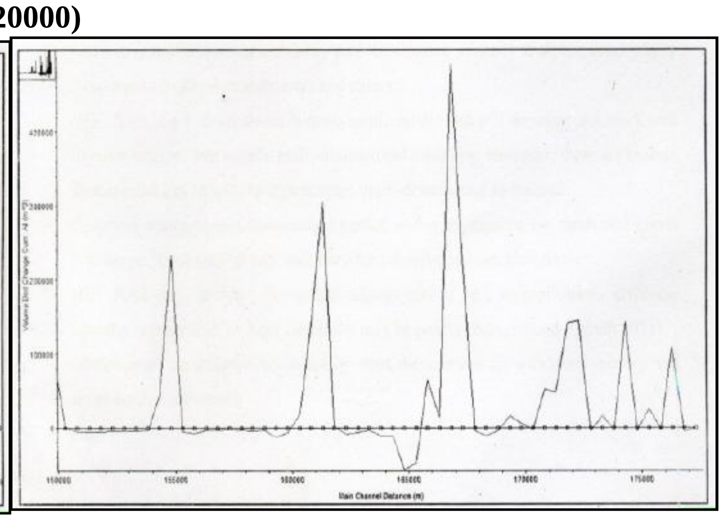


FIG. 19 Net Volume Change (for Chainage 120000-150000) FIG. 20 Net Volume Change (for Chainage 150000-177500)

Reviewing the results from HEC RAS model runs for Quasi Unsteady flow conditions, it was noticed that the erosion of bed was carried out for chainage 115000-121000, 128000-147000, 150000- 161000 and deposition was carried out for chainage 0-115000, 121000-128000, 147000-150000. 161000-177500 (Fig. 8.15.a-e) Further it was observed that erosion was carried out in above stated reach due to increasing flow velocity and shear stress on the sediment particles. Sediments were deposited in the above staled reach mainly because of detention in velocity of flow in the respective river reach.

The net volume change throughout the main reach was integrated. The total volume was calculated as:

Total volume = deposition + erosion

The final result was deposition i.e. sedimentation of 5.14Mm^3 /area. The sediment area of reservoir was considered as 74.473 Mm^2 (Using SRST analogy). Thus the total sedimentation volume was estimated as 382.645 Mm^3.

LIMITATIONS OF MATHEMATICAL MODEL

1) Vast data requirement
2) Users may find numerical instability problems during unsteady analyses. especially in sleep and/or highly dynamic rivers and streams
3) HEC-RAS is a l-dimensional hydrodynamic model and will therefore not work well in environments that

require multi-dimensional modeling. However, there are built-in features that can be used to approximate multi-dimensional hydraulics

4) Sediment transport uses continuity equation and is appropriate for sands and gravel size range. So additional care necessary for cohesive and complex flows
5) HEC RAS only accounts for vertical adjustments of bed, so applications involving lateral migration and / or bank instability may be poorly characterized (Gareth 2011)
6) Modeling of the structure is limited by what the user can do with cross sections and water surface elevations

CONCLUSION

Satellite Images were delineated to calculated loss in capacity of reservoir in Satellite Remote Sensing Technique. Present Total sedimentation in the reservoir using SRST was estimated at 422.196 Mm^3. Also the topography generated in the Mathematical model HEC-RAS was run for Quasi Unsteady flow conditions and the present total Sedimentation in the reservoir was estimated at 382.645 Mm^3. Both the estimated values of sedimentation are fairly comparable.

The sources for errors might be the Low resolution of satellite imagery i.e. 30m for SRST. The water spread area delineation might get affected due to it, consequently affecting reservoir capacity calculations. In HEC RAS model, cross sections were generated using toposheets. Toposheets elevations might differ from actual present elevation as toposheets were constructed a long time back. Incomplete Gauge discharge data for the years 2003, 2004, 2007, 2008. 2011, 2012, 2013 might be a source of error. The mathematical model was run for period 1987-2010. Whereas the remote sensing studies were done from 1977-2013 This can also be a reason for comparatively lesser volume of sedimentation using the mathematical model. Also the assumptions followed in mathematical modeling are based on theoretical concepts.

The further studies on the same subject may be carried out for better results with additional data if available. The above methods are widely used for Reservoir Sedimentation studies. The selection of the method is based on the availability of data required for the studies. In some cases the required data is not available because either gauging site is not located nearby reservoir area or the study reach is not accessible. For this situation, the estimation of sedimentation is to be carried out using Satellite Remote Sensing Technique. The method to develop one dimensional mathematical model in HEC RAS is to be adopted where the river gauging stations are available in the nearby reservoir area, so that flow data and sediment data required for the mathematical model are easily available.

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