CHAPTER 6

SEDIMENT TRANSPORT MODELING OF RIVER GANGA NEAR VARANASI

6.1 INTRODUCTION

Sediment transport in the river is a complex process that depends on different factors like; hydrological factor, river cross-section, etc. The natural behaviour of the river significantly depends upon the erosion, deposition and transportation of sediments. Therefore, modelling sediment transportation will help to predict the nature of the river. Sediment transport modelling of river Ganga near Varanasi is considered in this study. This chapter details the methodology used for modelling, results obtained with discussion is presented.

6.2 STUDY AREA

For modelling the sediment transport total of fifteen cross-sections were selected. A detailed description of these cross-sections has been presented in subsection 3.2.3 of chapter 3.

6.3 METHODOLOGY

Sediment transport modelling in the present study was done with the help of the HEC-RAS 5.0.7 software package. This is open-source software used for modelling sediment transportation, flood, etc. The detail of the methodology as flow chart is presented in Figure 6.1. At the first stage of modelling in HEC-RAS, some specific input data were collected and then entered. Digital Elevation Model (DEM), hydraulic, hydrological and sediment data are required as input in HEC-RAS for sediment transport modelling. After this,

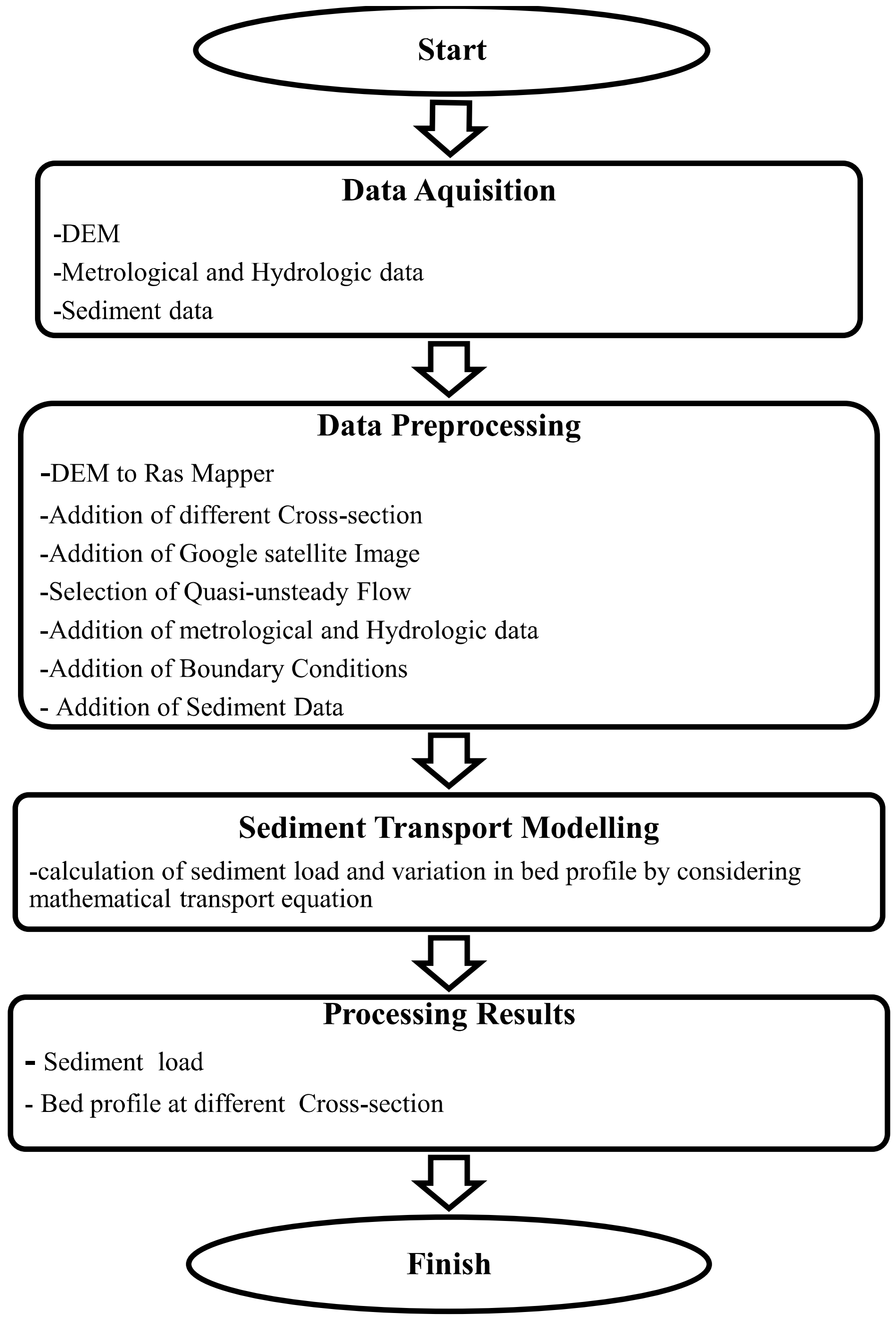

Figure 6.1 Methodology used for sediment transport modelling

different data processing was done like; preparation of Ras-Mapper with the help of DEM, the addition of different cross-sections considered in the study, the addition of Google satellite image, and selection of flow condition as Quasi-unsteady flow addition of boundary condition, the addition of hydrologic, hydraulic and sediment data. After the processing, sediment load and cross-section was obtained as output. The details of the study area, data collected, and process are discussed in the following section.

6.4 DATA ACQUISITION

As discussed earlier, for modelling the sediment transport behaviour, input data were entered as in put in HEC-RAS. Data entered in modelling are: (a) DEM Data of stretch (b) Metrological and Hydrological Data (c) Sediment Data. Details of these data used are presented in the following subsections.

6.4.1 DEM DATA

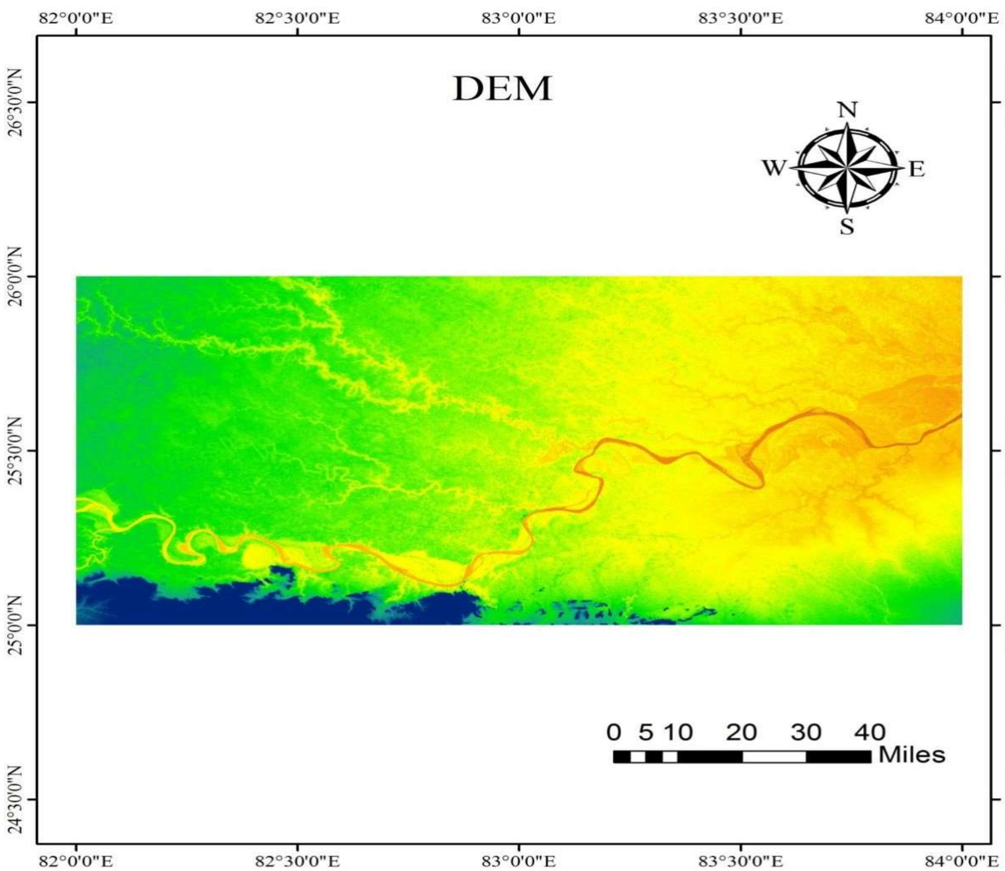

Figure 6.2 DEM of the Study area

DEM is a digital model or 3D model, which includes terrain surface and elevation data (Butt et al. (2015). DEM data was collected from the website of the United States Geological Survey (USGS). The DEM was prepared by mosaicing two maps (n254_e082 and n24_e083) obtained from the USGS. DEM can be presented in two ways, in raster form or vector-based triangular irregular network (TIN). The DEM used is SRTM DEM. 30 m resolution of the DEM data obtained from USGS is presented in Figure 6.3

6.4.2 METROLOGICAL AND HYDROLOGICAL DATA

Metrological and hydrological factors influence the sediment transport process. So, it is essential to use the metrological and hydrological data as input in HEC-RAS. Figure 6.3 shows the variation of temperature for ten years from 2008 to 2018. The temperature data presented here indicates the temperature of river water. In the region selected for the study, it is found that May and June are the hottest, while December and January are found generally coldest. Temperature variation in the river was found about 16^{o}C to 18^{o}C in a particular year. A higher water temperature was found in the study region before the monsoon, while a colder temperature was observed after the monsoon.

Hydrological data used as input in modelling are presented in Figure 6.4 and 6.5. Hydrograph data used in this study were obtained from the Department of Central Water Commission. Flow-Hydrograph of the study area is illustrated in Figure 6.4. Flow-Hydrograph represents the discharge in the river over time. River flow discharge of ten years duration from 2008 to 2018 is shown on the vertical axis of Figure 6.3. Stage-Hydrograph of the study area is presented in Figure 6.4.

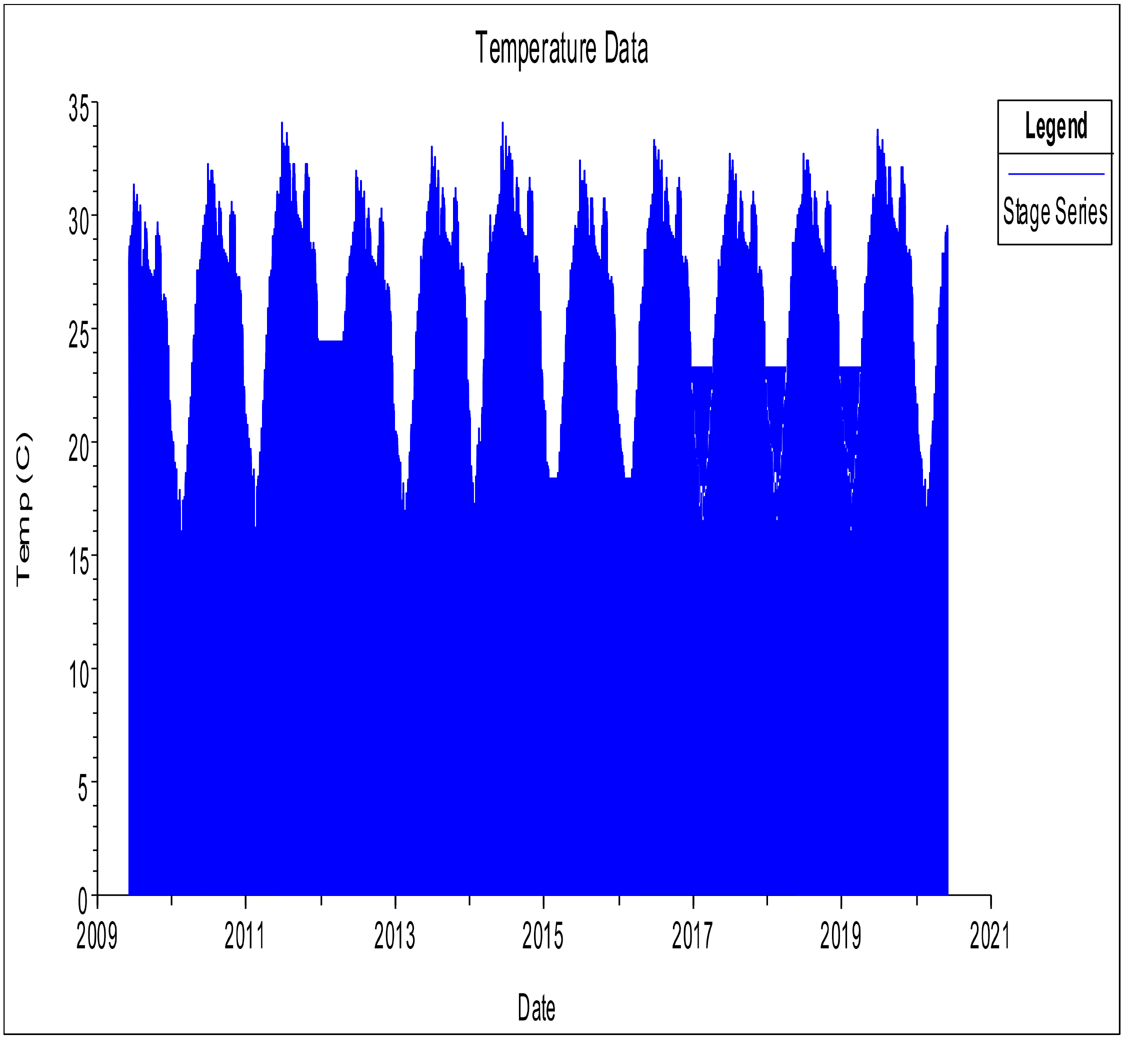

Figure6.3 Temperature series data of study area

Stage-Hydrograph represents the level of water in the river. Water level for ten years in the river from 2008 to 2018 is shown on the vertical axis in Figure 6.6. From both hydrographs, it can be observed that peak discharge or water level in the study region mainly occurs in August to September. This happens due to the rainfall during Monsoon. In the Monsoon season, heavy rain occurs for this reason. Rainfall in Monsoon varies from year to year. Due to this, it can be observed that the peak of the hydrograph differs significantly.

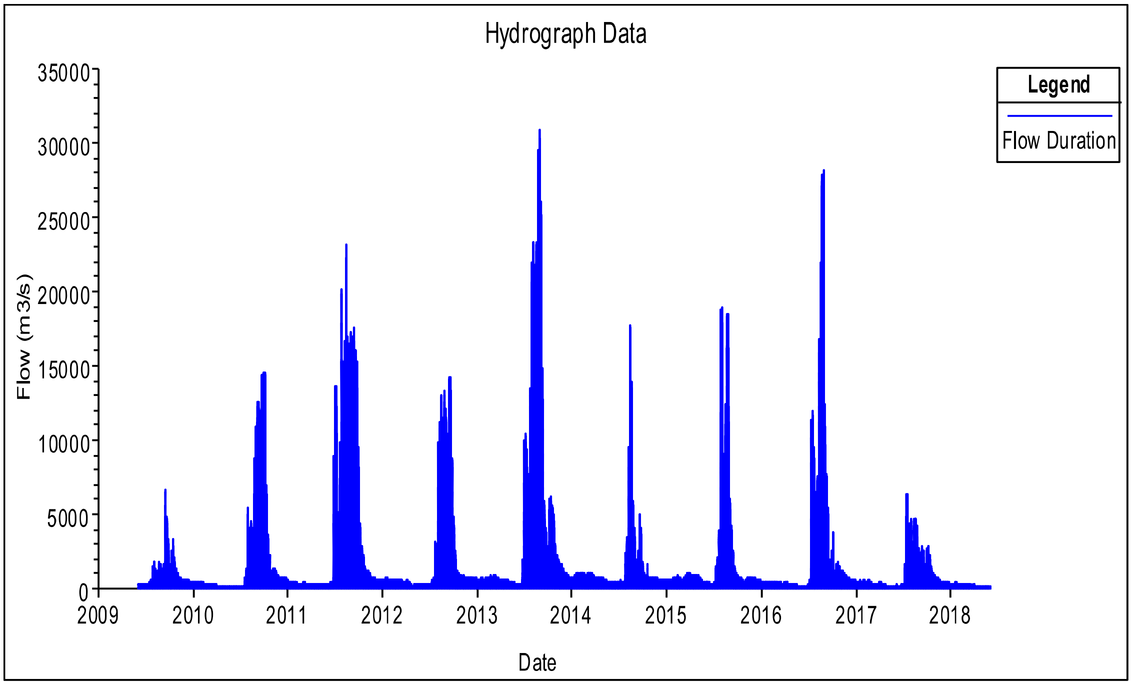

Figure 6.4 Flow-Hydrograph of the study area

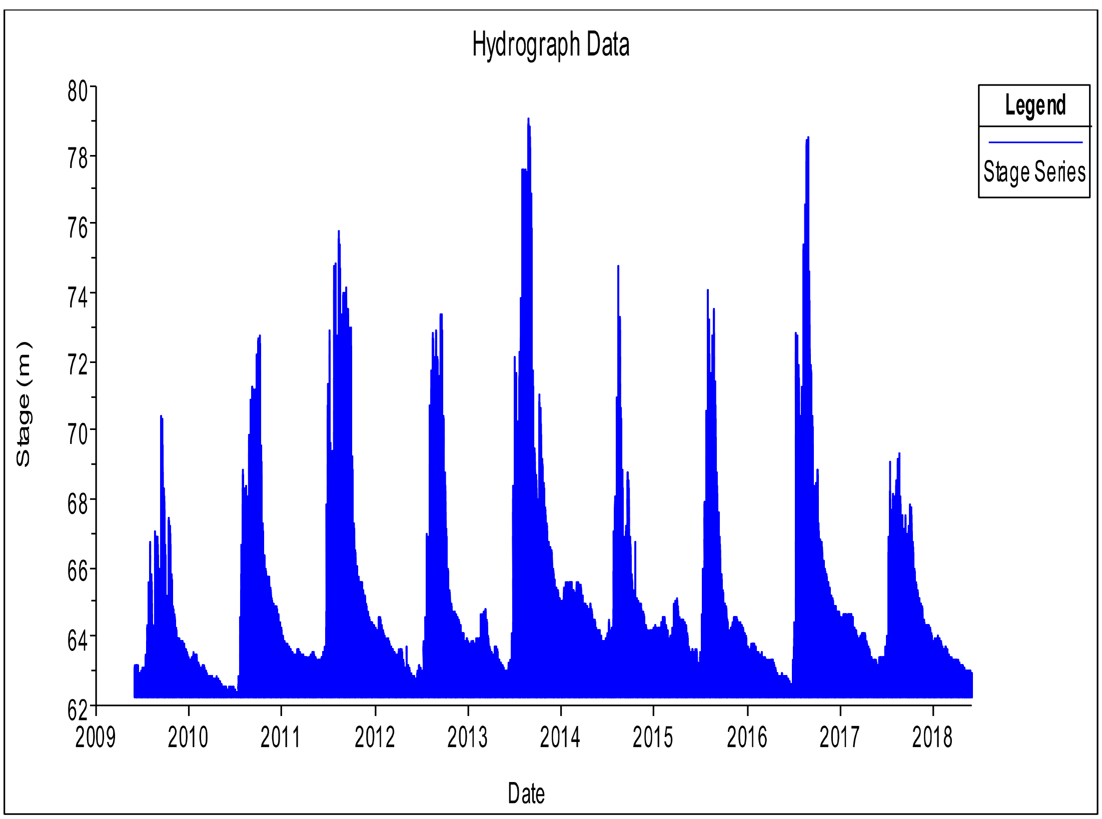

Figure 6.5 Stage-Hydrograph of the study area

6.4.3 SEDIMENT DATA

The sediment related data is an essential input for the modelling, and Figure 6.6 shows the sediment rating curve of the sediments present in the river water. The sediment rating curve indicates the relationship between the flow and the sediment load. The river flow in Figure 6.6 is presented on the horizontal axis, while a load of sediments in water is shown on the vertical axis. It can be observed that sediment load is directly proportional to the flow. Data of sediment load was obtained from the CWC. At higher flow, turbulence in water increases. Due to this, sediment carrying capacity gets increased. Also, at high flow condition erosion process get increased. But in the lien period, i.e. at low flow condition tendency of deposition of sediments get increased.

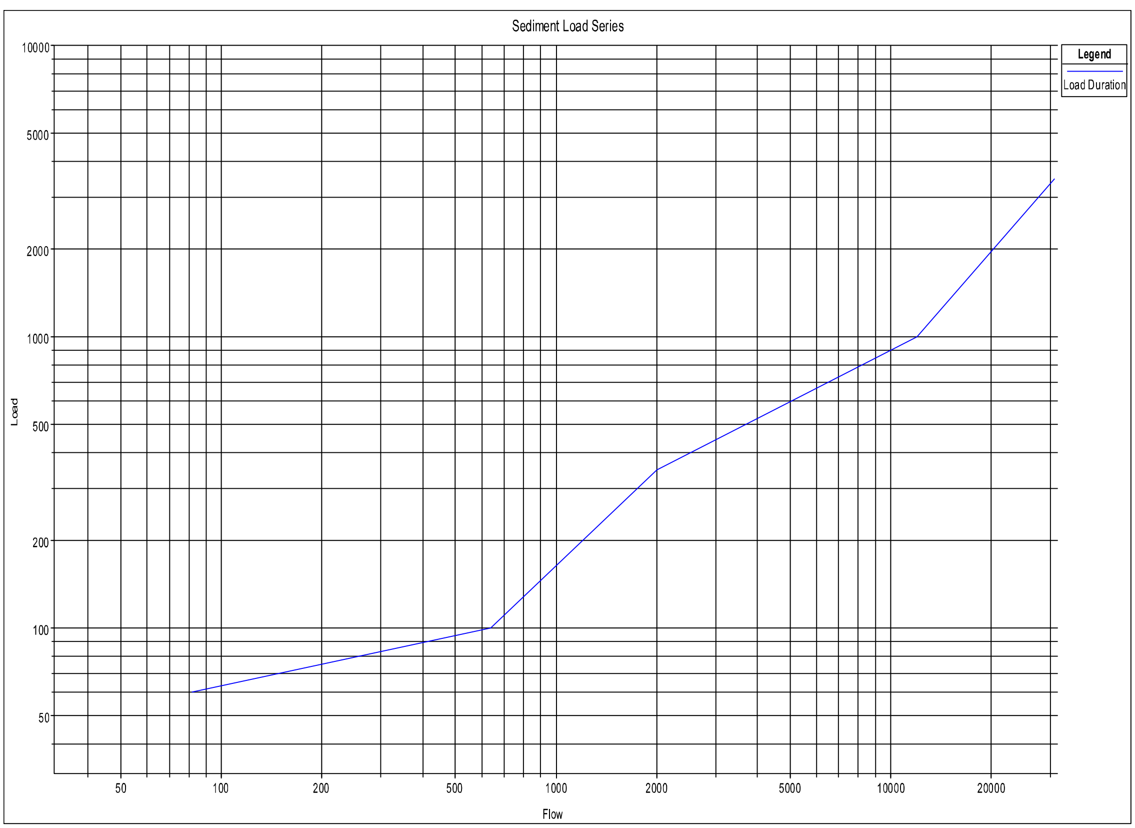

Figure 6.6 Sediment rating curve

6.5 DATA PROCESSING

Different data processing must be done for sediment transport modelling, as mentioned earlier (Figure 6.1). The details of the processes are discussed in the following sub-section.

6.5.1 DEM TO RAS-MAPPER

DEM mentioned above was used as input for RAS-Mapper in HEC-RAS. In DEM, data elevation of different points is included. But it doesn’t have the depth of bed below water level. So through the ESRI projection file coordinate, other attributes of the DEM image were aligned. After this, the map layer was created with the help of satellite data. Figure 6.7 shows the RAS-Mapper prepared by the DEM of the study area considered in the study.

RAS-Mapper allows user to create a different form of geometry and required cross-sections.

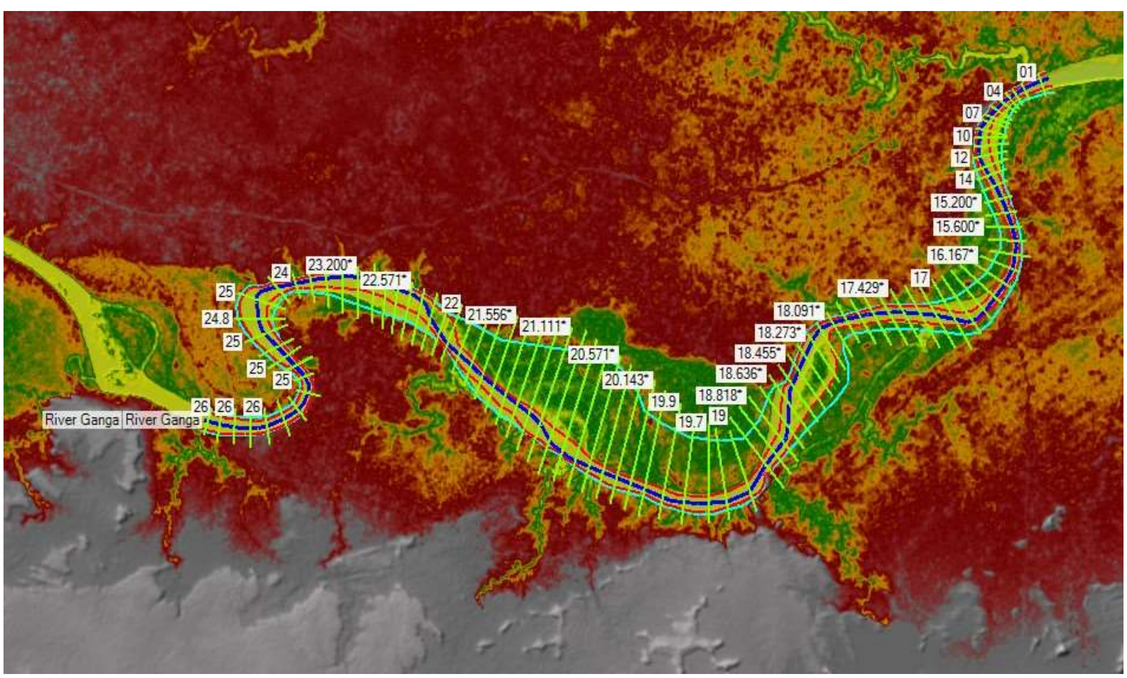

Figure 6.7 RAS-Mapper of the study area

6.5.2 ADDITION OF DIFFERENT CROSS-SECTION

The geometry tool of RAS-Mapper is used for drawing bank line, flow path, cross-sections. The river flows between two lines during the average discharge period, known as the 'bank line' indicated with the red line'. Flow path lines are boundary lines, which defines the flood plain region (green line). Fifteen cross-sections were prepared by adding data of cross-section profile obtained from the ADCP (Appendix-A). Along with cross-sectional data and Manning's value of the main channel, the left bank and the right bank was also used in RAS. Figure 6.8 shows the different geometries entered in the RAS-Mapper. It also includes terrain in the surrounding of the stretch considered in the study. Figure 6.9 shows the 3D multiple cross-section plot of all fifteen cross-sections.

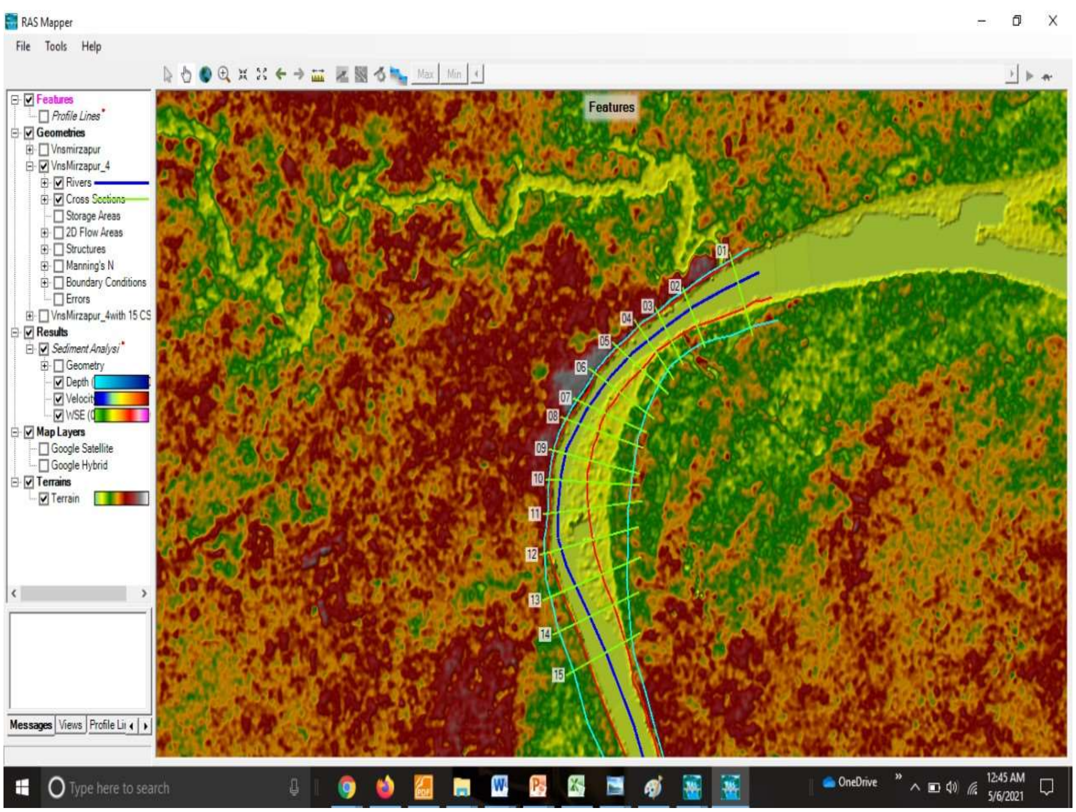

Figure 6.8 Region near Varanasi under consideration for study

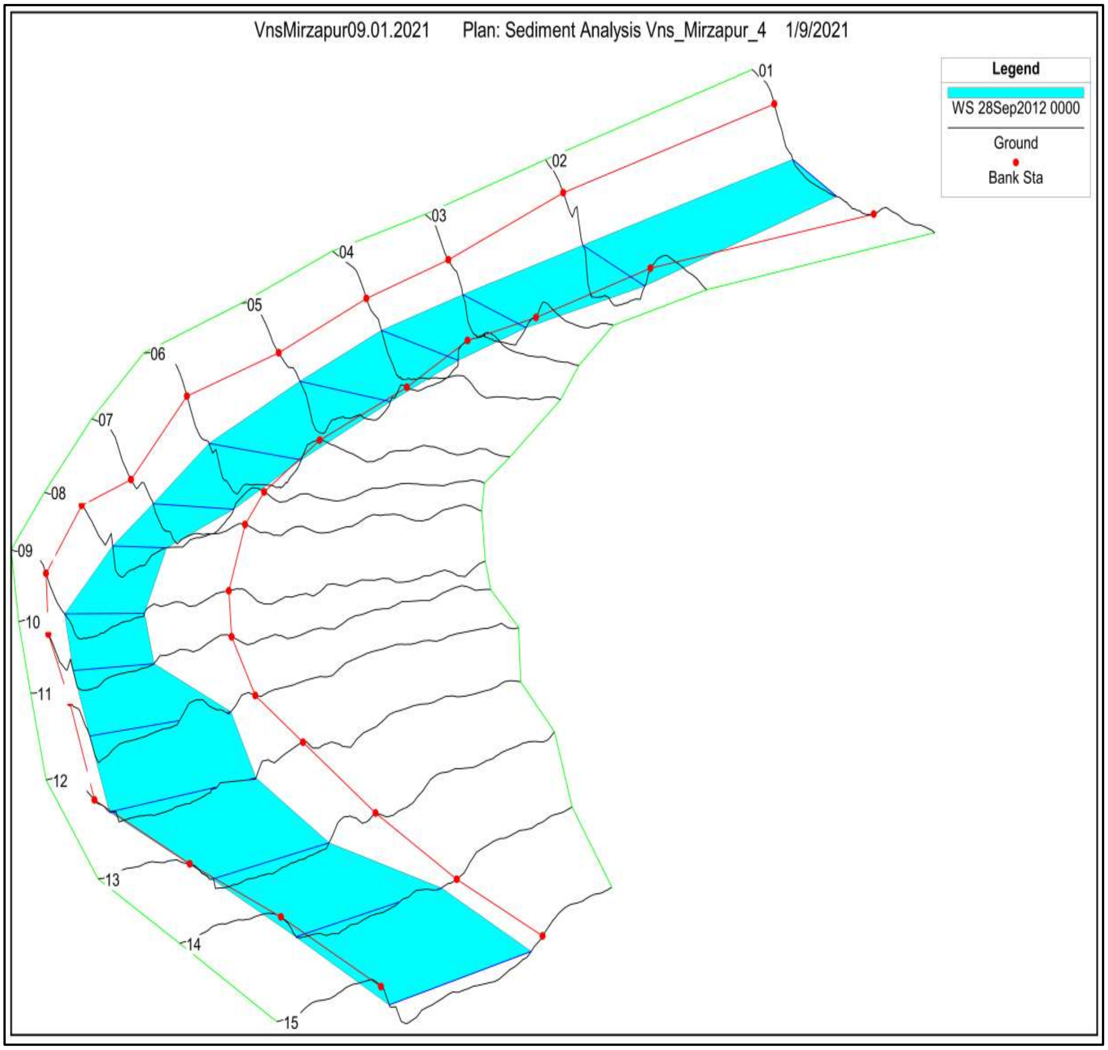

Figure 6.9 Prospective plot of different sections through HEC-RAS

6.5.3 ADDITION OF GOOGLE SATELLITE IMAGE

Google satellite images were added to the RAS-Mapping. Due to this additional locality of the study visible on Map. Figure 6.10 shows the RAS mapping and Google satellite image of the stretch considered along with the cross-sections. The different places of the Varanasi are visible in Figure 6.10.

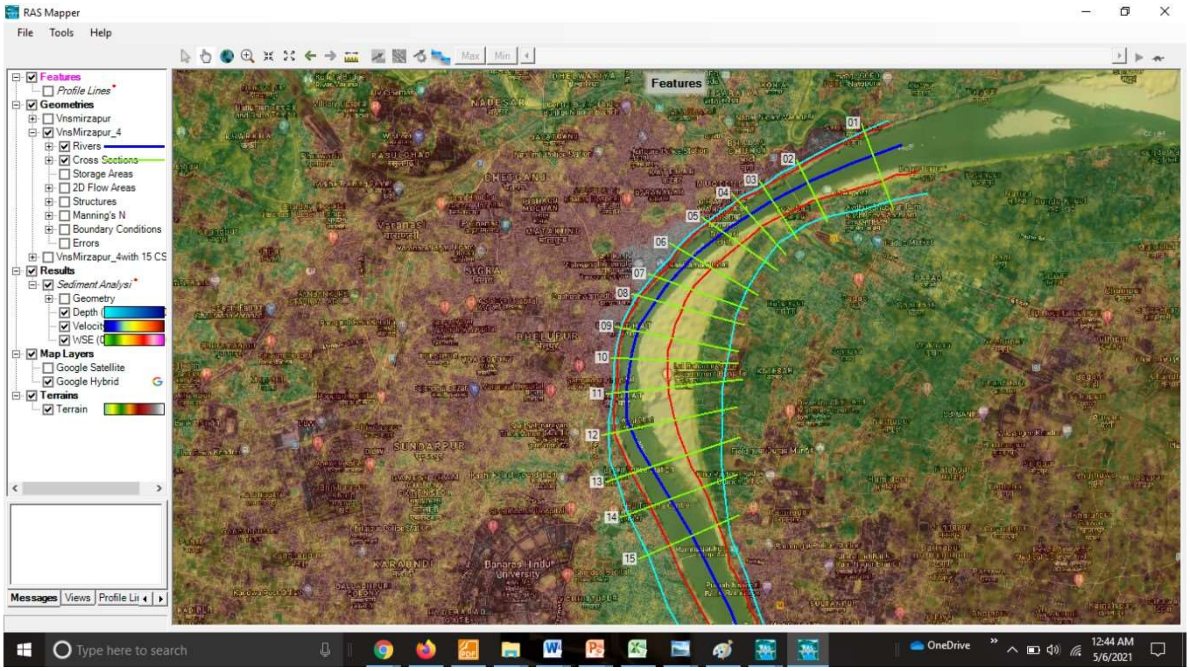

Figure 6.10 RAS-Mapper of the study area with Google satellite image.

6.5.4 SELECTION OF FLOW TYPE

Three types of flow option are available in HEC-RAS, which are (i) Steady flow (ii) Quasi-unsteady flow (iii) Unsteady flow. In steady flow, flow parameters don't change with time. For unsteady flow, different flow parameters change with time. Quasi-unsteady flow is basically a flow type model in which a hydrograph is added with the steady flow parameter. For sediment transport modelling or flood mapping, Quasi-unsteady flow is most suitable Salajegheh et al. 2009, Mustafa et al. 2017, etc.

6.5.5 ADDITION OF METROLOGICAL AND HYDROLOGICAL DATA

Metrological data, i.e., temperature data, were used in HEC-RAS through Quasi-Unsteady flow editor (Figure 6.3). Hydrological data (Figure 6.4 and 6.5) were also entered with the same Quasi-Unsteady flow editor. Figure 6.11 shows the window of the Quasi-unsteady flow editor.

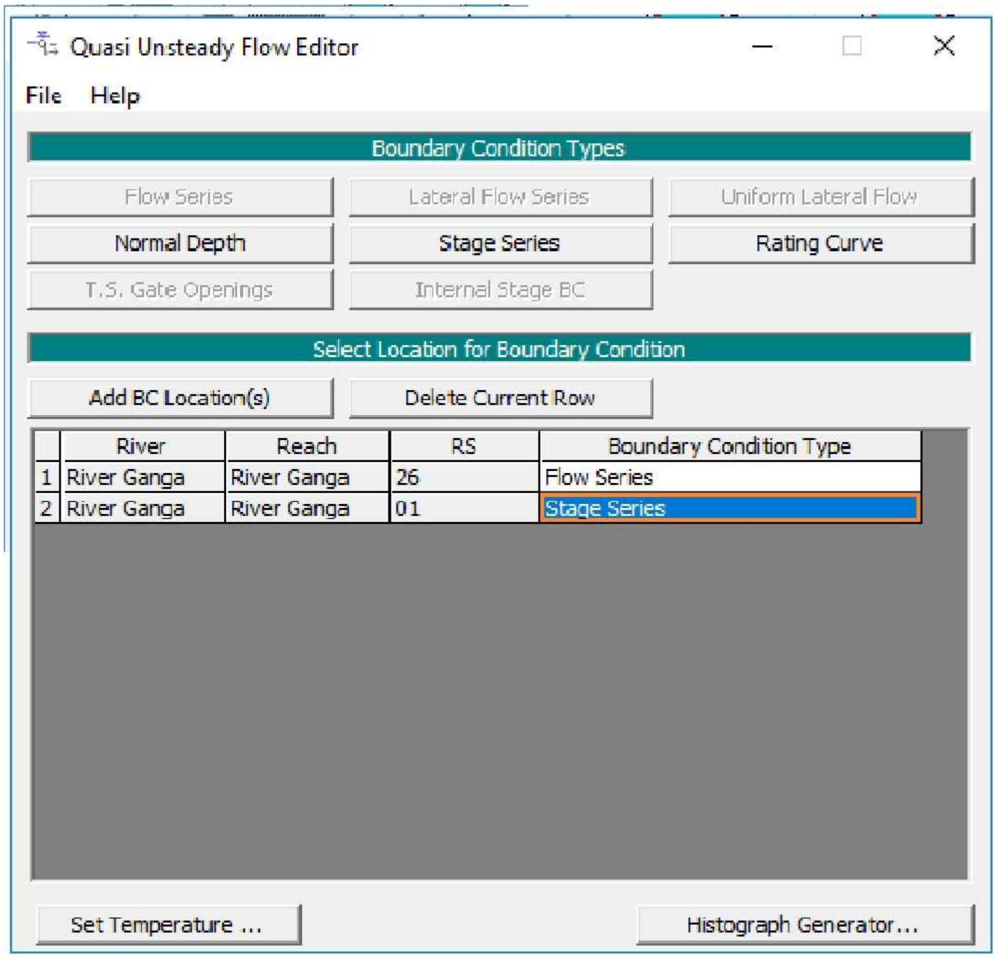

Figure 6.11 Quasi-unsteady flow editor of HEC-RAS

6.5.6 ADDITION OF BOUNDARY CONDITION

For modelling purpose selection of boundary condition is an important step. For upstream boundary condition, flow series is entered. Flow series includes data of discharge, flow duration, computational increment based upon flow. For downstream boundary condition, three options for data entering are available: normal depth, stage series, and rating curve.

Stage series were used for downstream boundary condition. In stage series, stage, i.e. water along with stage duration, were entered. The data used for this are presented in Figure 6.5.

6.5.7 ADDITION OF SEDIMENT DATA

Sediment data discussed in section 6.2.3 is entered in the sediment data tool of HEC-RAS. In this, initial conditions and transport were entered as input. In the initial condition bed, the gradation of sediment was entered. Also, transport function, sorting method and flow velocity method was selected. In the transport function, eight types of options were available. Meyer Peter Muller (MPM) transport function was selected for modelling . MPM was developed equation (6.1) after conducting a large number of experiment with uniform grade and light weigh the material. Here, equation 6.1 is based on the median particle diameter with mixed sediment particle and shear stress. Where manning's roughness calculated based on median particle diameter shown in equation 6.2. The development expression based on the flume experiment but still have covered the large area. The equation is given below Meyer-Peter and Muller (1948):

$$q_b = \left(\frac{\rho_s}{\rho_s - \rho}\right).8.\left(\rho^{-1/2}\right).\sqrt[3]{\left[\sqrt[3]{\left(\frac{n_{Grain-roughness}}{n_{Total-roughness}}\right)}.\tau_b - 0.047(\rho_s - \rho)g.D_{50}\right]} \tag{6.1}$$

Where, q_b= unit weight/second/ unit width of channel,

q_b= Density of water

ρ_s= Density of sediment

D_{50} = Median particle diameter

τ_b = Boundary Shear stress

n = Represents Manning's

$$n_{Grain-roughness} = 0.0151\, D_{50}^{1/6} \tag{6.2}$$

All the transport functions were tried for the prediction of sediment transport. It was found that the Meyer Peter Muller function gives the best result.

6.6 RESULTS AND DISCUSSION

Results obtained from the HEC-RAS modelling and from direct measurement are presented in the following three subsections. In the first subsection, results obtained from the direct measurement is presented. In the second subsection, results obtained from the HEC-RAS modelling is presented. The Validation of the data obtained from the modelling is done by comparing it with the data obtained from the direct measurement. The validation of the output is presented in the third subsection. Results obtained were presented in terms of the variation of the cross-section and sediment concentration with time.

6.6.1 RESULTS OBTAINED FROM DIRECT MEASUREMENT

Data of cross-section at Mirzapur and Varanasi obtained from direct measurement is presented in Figure 6.12 to 6.15. The data of cross-sections were measured during pre-monsoon and post-monsoon season. Figure 6.12 shows the bed profile of the cross-section at Mirzapur from 2008 to 2018 during the pre-monsoon season. Elevation of different points on the bed is presented on the vertical axis. The distance shown on the horizontal axis is measured from the left bank. It can be observed that significant variation in the river bed elevation in the part of the section lies between 300 m to 1150 m from the left bank. Variation in the river bed or around 8 m in this section can be observed from Figure 6.12. And water flows through the year. But in the rest of the sections from the left bank to 300 m and after 1150 m to the right bank, no flow condition exists during the lien period. Because of this, significant variation in river bed takes place in the section between 300 m to 1150 m from the left bank, while in another part of the river, no significant variation occurs. Further, it has been observed that in the section between 300 m to 600 m from the left bank, which is nearer to the left bank and in part between 1000 m to 1150 m which is nearer to the right bank, erosion is taking place. While in the centre part, which lies between 600 m to 100 m, deposition is taking place.

Figure 6.12 shows that the left bank has a mild cross-sectional slope, while the right has a steep cross-sectional slope. The river elevation was 83 m at the left bank, and after the distance of 200 m elevation became 73 m, but near the right bank, 73m elevation reached only at a distance of 50 m. Since the left bank of the river is on the river's convex side, deposition is taking place on the left bank. So cross-sectional slope is mild in the left bank. The right bank is on the concave side of the river, due to which erosion takes place. Because of this, the cross-sectional slope in the right bank is steeper. The bed profile of the cross-section obtained from the direct measurement at Mirzapur during the post-monsoon season is presented in Figure 6.13. Similar to the pre-monsoon season, the significant variation in bed profile can be observed in the section between 300 m and 1150 m. By comparing Figure 6.12 and 6.13, it can be concluded that there is no significant difference occurs in the cross-section between the pre-monsoon period and post-monsoon period. The considerable variation observed in the 2011 bed profile where post-monsoon shows the depositional characteristic compared to the other cross-sections.

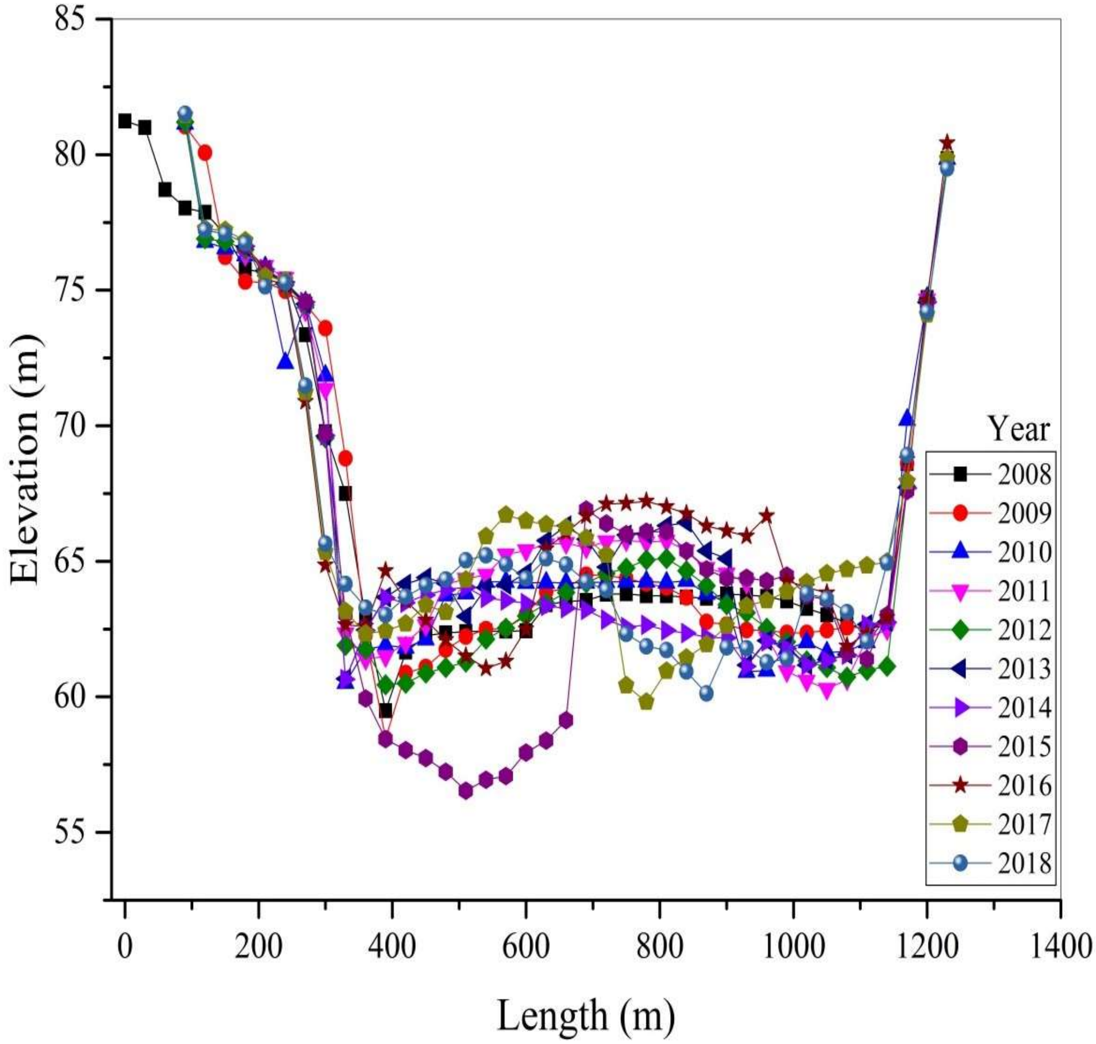

Figure 6.12 Bed profile of Mirzapur cross-section during pre-monsoon season

The bed profile of the cross-section near the Varanasi during the pre-monsoon season and the post-monsoon season is depicted in Figure 6.14 and Figure 6.15. Bed profile of the cross-section presented here is for ten years from 2008 to 2018. It can be observed from both of the Figure that significant variation in bed occurred in the part of the section between 130 m to 650 m from the left bank. A variation of around 12 m can be observed in Figure 6.14.

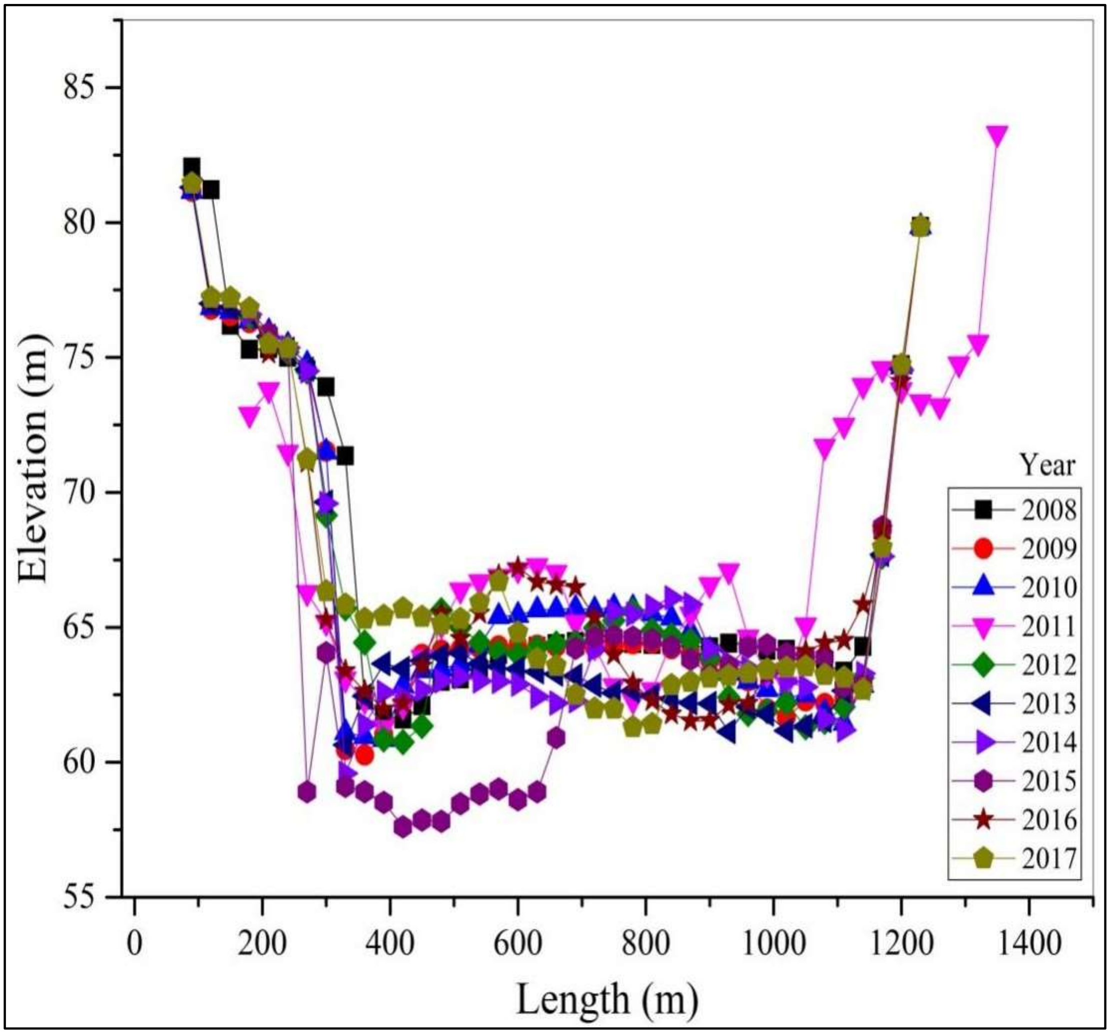

Figure 6.13 Bed profile of Mirzapur cross-section during post-monsoon season

It can be observed that the cross-sectional slope of the river on the left bank side is steeper, while the cross-sectional slope on the right bank side is mild. The mild slope in the right bank is due to the deposition of sediments, while the erosion of the left bank forms a steep slope. The right bank is on the convex side of the river, causing deposition on the right bank. Erosion on the left bank takes place because it is on the concave side of the river. It can be further observed that from 2008 to 2018, overall erosion is taking place in the bed of the river. Bed-profile from 2014 to 2018 shows the clear formation of the double depression in the river bed. Such depressions are not visible in the early years from 2008 to 2011.

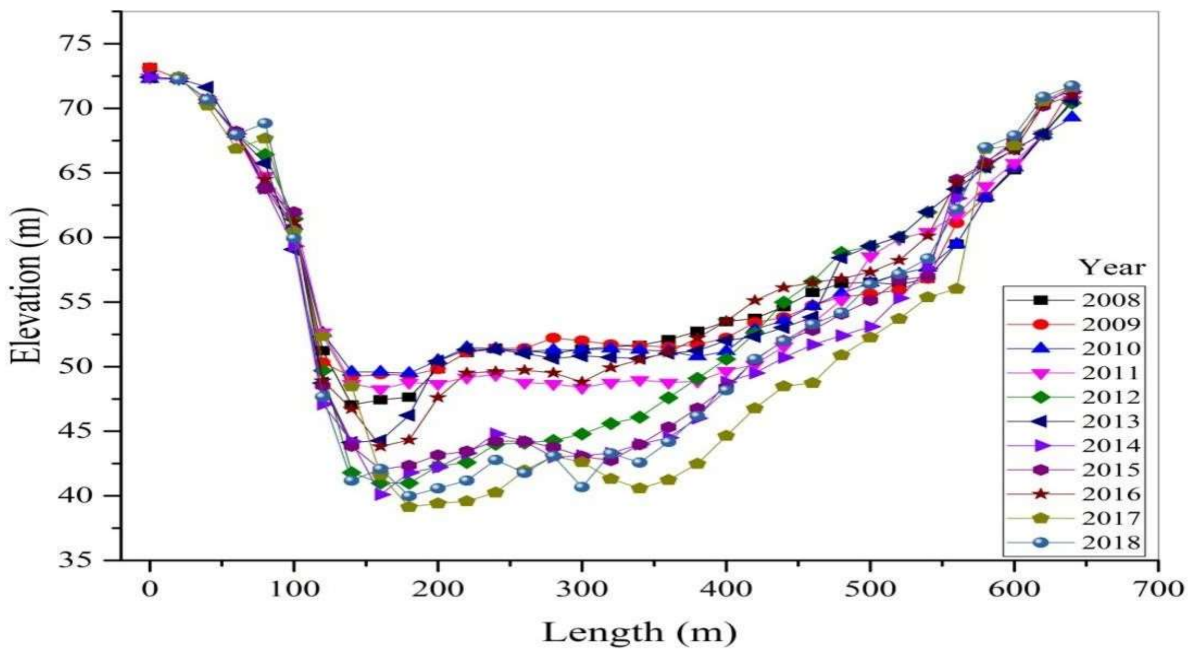

Figure 6.14 Bed profile of Varanasi cross-section during pre-monsoon season

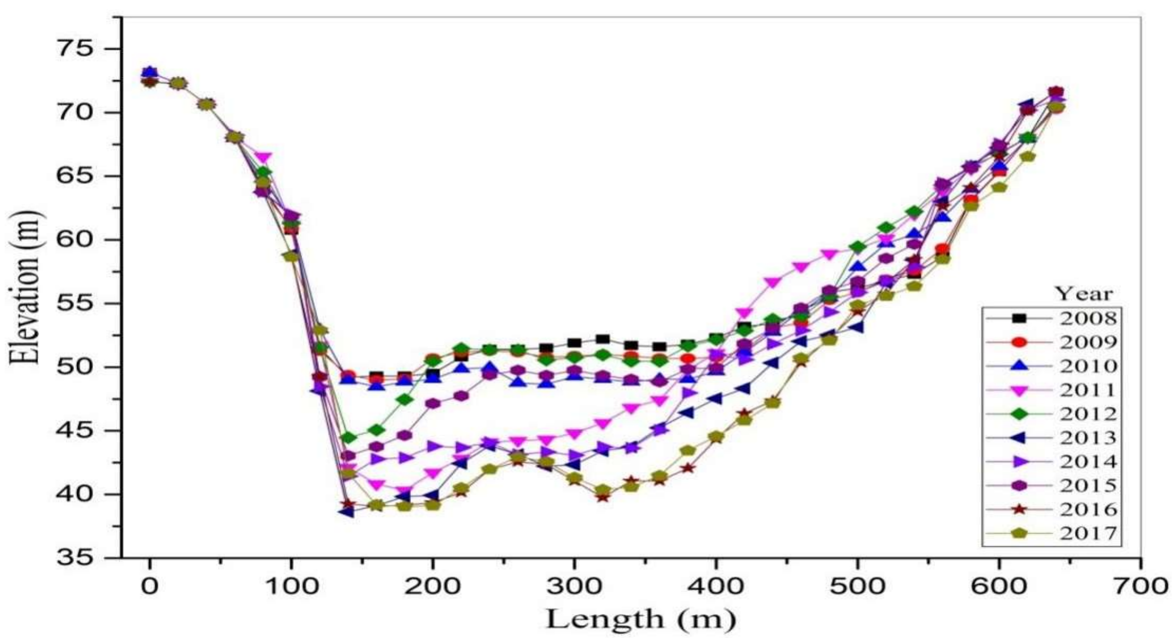

Figure 6.15 Bed profile of Varanasi cross-section during pre-monsoon season

The sediment load at the cross-section near Mirzapur and Varanasi is presented in Figure 6.16 and 6.18, respectively, from 2008 to 2018. Sediment concentration is shown on the vertical axis, and time is shown on the horizontal axis. In Figure 6.15, it can be observed that in all the year, peak sediment was observed in the month between August to September since this is the duration when high flow condition occurs. In the lien period, sediment concentration was found due to low flow condition. Similar behaviour of concentration of sediment can be observed for the cross-section at Varanasi. It can be further observed that peak sediment concentration at the cross-section near Mirzapur in most of the year lies in the range of about 400 mg/l to 2000 mg/l. At the same time, the cross-section near Varanasi lies in the range of about 500 mg/l to 2400 mg/l. Also, most of the year, sediment concentration at the cross-section near Varanasi is higher than the cross-section near Mirzapur. The possible reason for this lies in the difference in the geological condition of both cross-sections. Mirzapur is situated near to Vindhyan range, which has rocky strata. But between Mirzapur and Varanasi cross-section, most of the region is agricultural land. It may result in fewer amount sediments generated due to erosion. On the other hand, the presence of agricultural land leads to a higher amount of sediments generation. Due to the generation of fewer sediments at the cross-section near Mirzapur, not much deposition occurs in the convex side (left bank) of the river. But in cross-section near the Varanasi, due to the relatively higher concentration of sediments, more deposition is observed in the river's convex side (right bank). This phenomenon can be confirmed by comparing the bank's slope shown in Figure 6.12 and Figure 6.14. The slope of the left bank of Mirzapur, which is on the convex bank, is steeper than the slope of the right bank of Varanasi, which is also on the convex bank. This show more deposition at the cross-section near Varanasi.

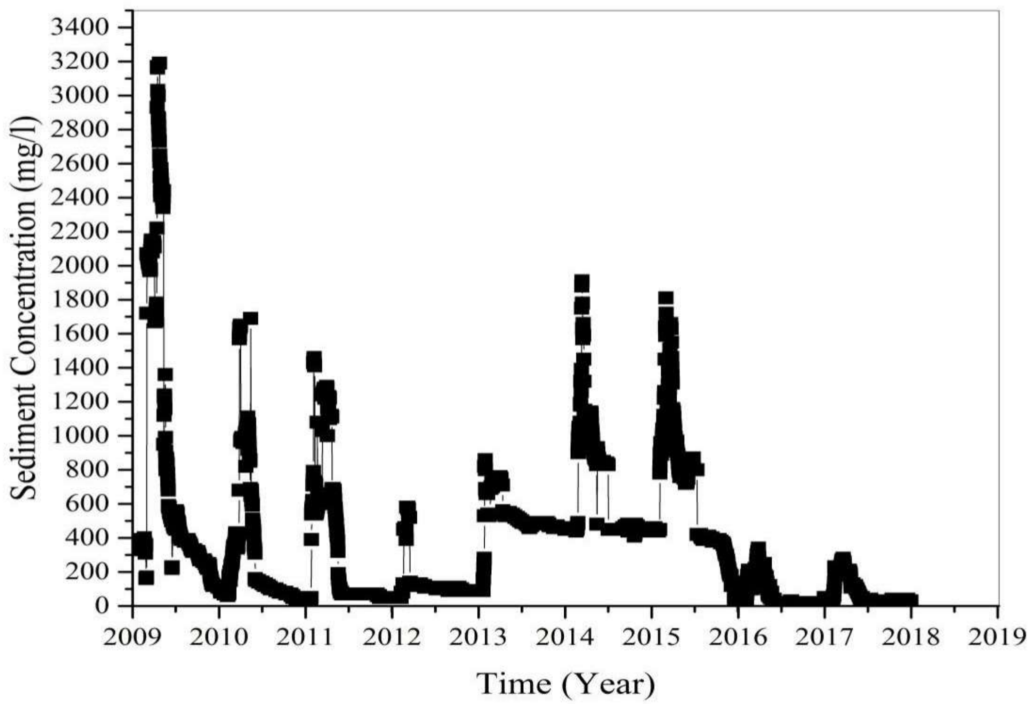

Figure 6.16 Sediment concentrations at Mirzapur

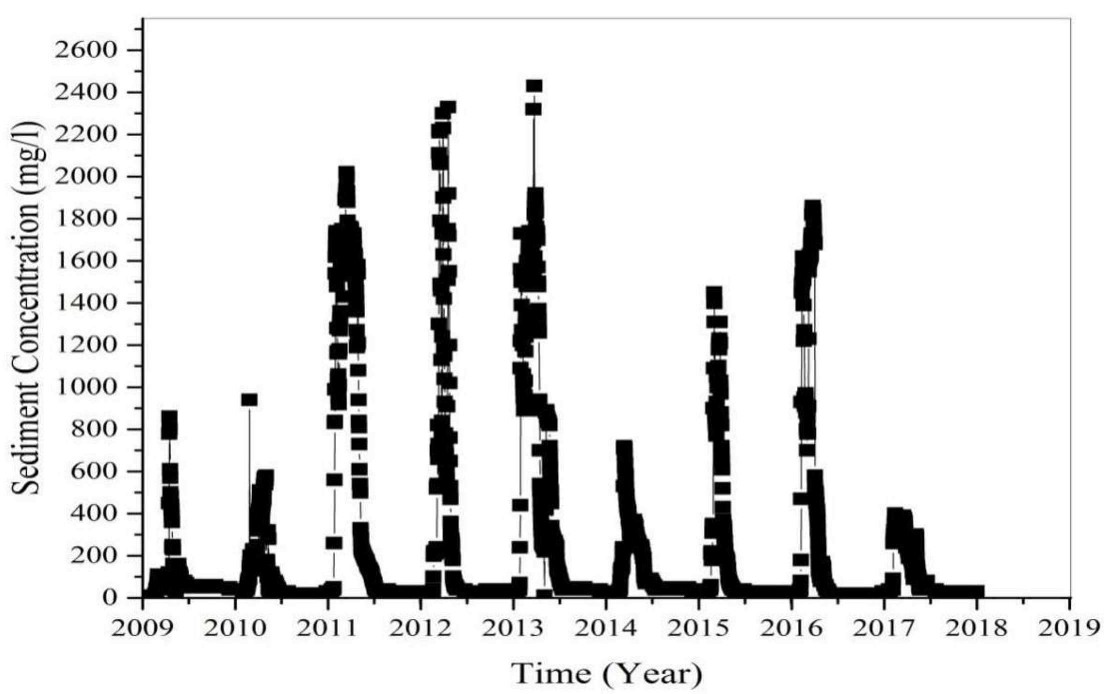

Figure 6.17 Sediment concentrations at Varanasi

6.6.2 RESULTS OBTAINED FROM HEC-RAS MODELING

As mentioned earlier, modelling of sediment transport is done with the help of HEC-RAS. The results obtained from the HEC-RAS is presented in terms of bed profile of cross-sections and sediment concentration. Bed profile of different cross-sections CS15, CS12, CS05, and CS02 are shown in Figure 6.18 to 6.21. For clarity, data of four years, 2009, 2012, 2015 and 2018, are presented in all these figures. The bed profile of CS15, which is present on the upstream side of the Varanasi, is shown in Figure 6.18. It can be observed that the slope of the bed at the left bank is steeper than the slope of the bed at the right bank. This finding is the same as found in actual measurement. It can be further observed that with year depth of channel bed increasing from 2009 to 2018. This shows that overall erosion of bed is taking place in river near Varanasi. A similar type of changes can be observed in Figure 6.20 to 6.22 for other cross-sections. Among all the cross-sections, a more significant variation in bed profile was observed for CS2. Figure 6.22 shows the bed profile of CS2 near Raj Ghat. In this section, the formation of double depression can be observed.

In Figure 5.7 of chapter 5, similar behaviour of this section was observed. Raj Ghat section is situated after the Malviya bridge. Also, at the distance of two kilometres from Raj ghat, Varuna river meets with river Ganga. Due to all these situations, sections near Raj Ghat become crucial, and higher erosion takes place. It can also be seen in Figure 6.21 that the depression formed near to left bank has greater depth than the right bank. Since the left bank of the CS2 is on the concave side of the river, more erosion is taking place in this part. Because of this, depression is more significant on the side of the left bank.

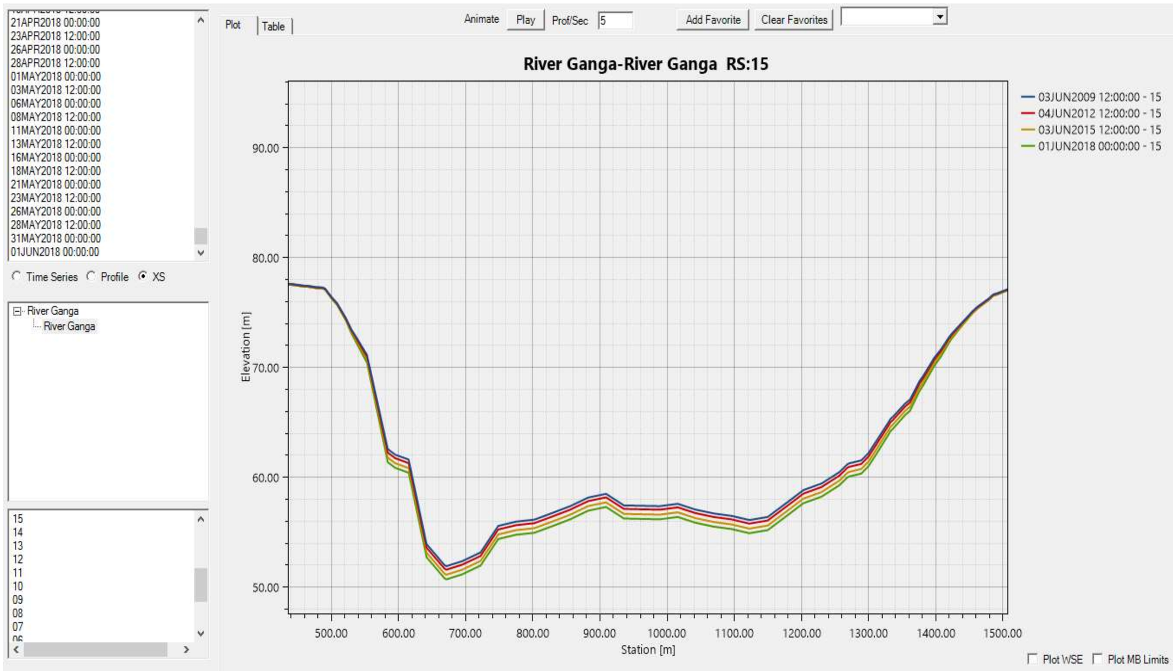

Figure 6.18 Bed profile of cross-section CS15 obtained from HEC-RAS

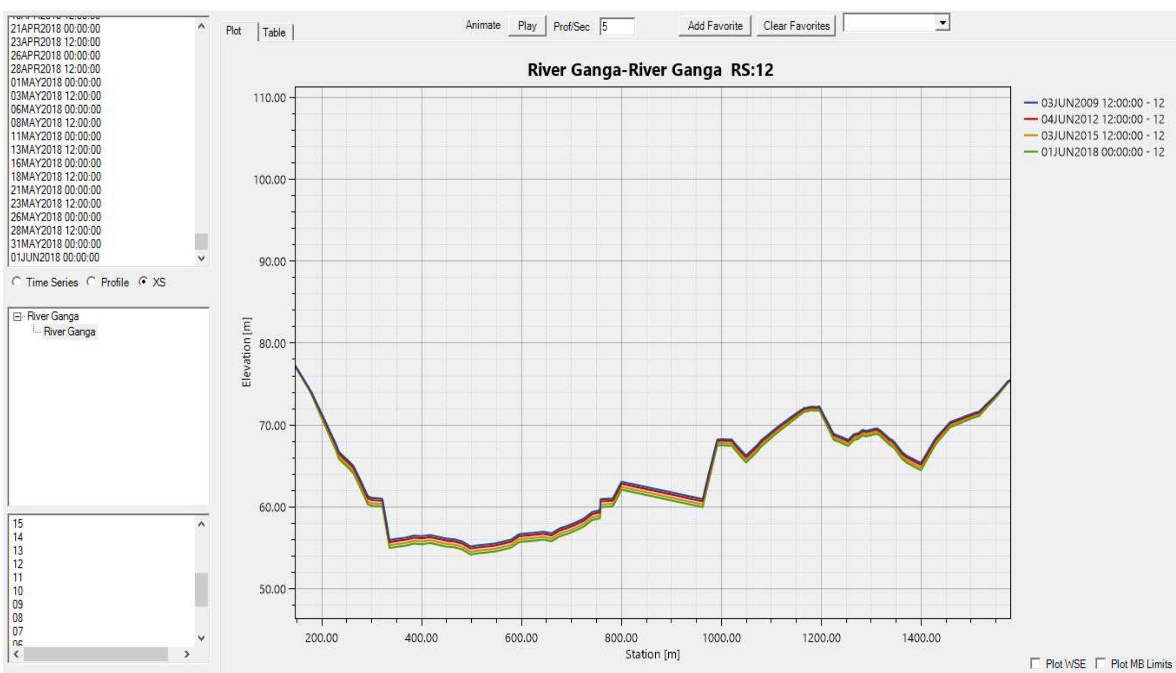

Figure 6.19 Bed profile of cross-section CS12 obtained from HEC-RAS

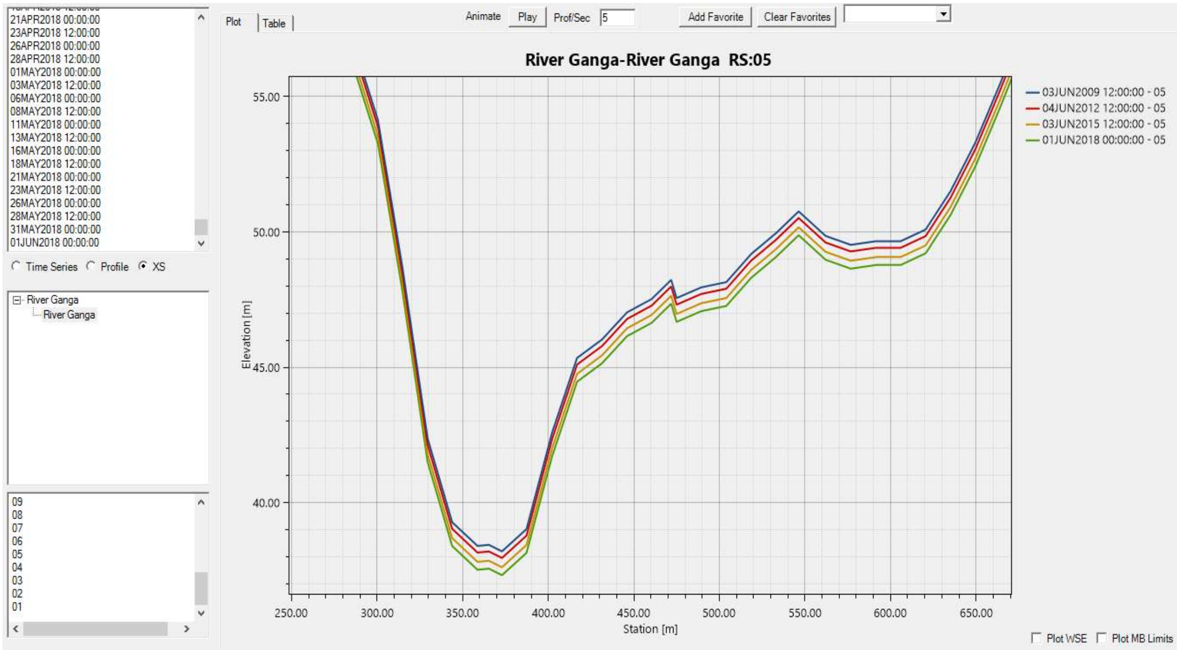

Figure 6.20 Cross-section profile of CS05 obtained from HEC-RAS

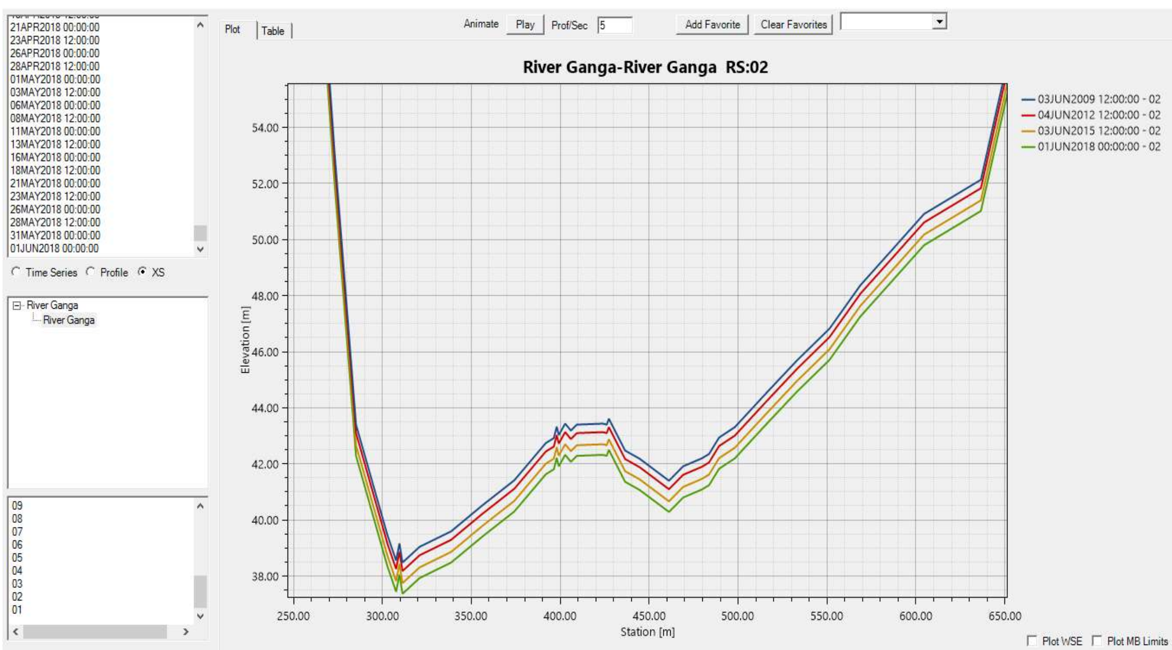

Figure 6.21 Cross-section profile of CS02 obtained from HEC-RAS

The results of sediment concentration obtained from the HEC-RAS modelling for the cross-sections CS 15, CS12, CS05 and CS02 is presented in Figure 6.22, 6.23 6.24 and 6.25, respectively (the year 2008 to 2018). It can be observed that results obtained from HEC-RAS modelling for all the cross-section show peak sedimentation during high flow condition. While during low flow condition, low sediment concentration can be observed. If the sediment concentration of different cross-sections (Figure 6.22-6.25) is compared, it can be observed that there is no much difference in magnitude. It shows that at any time, sediment concentration doesn't change in the cross-sections considered. Since all the cross-sections are near Varanasi, it can be concluded that sediment concentration doesn't change for such a short distance.

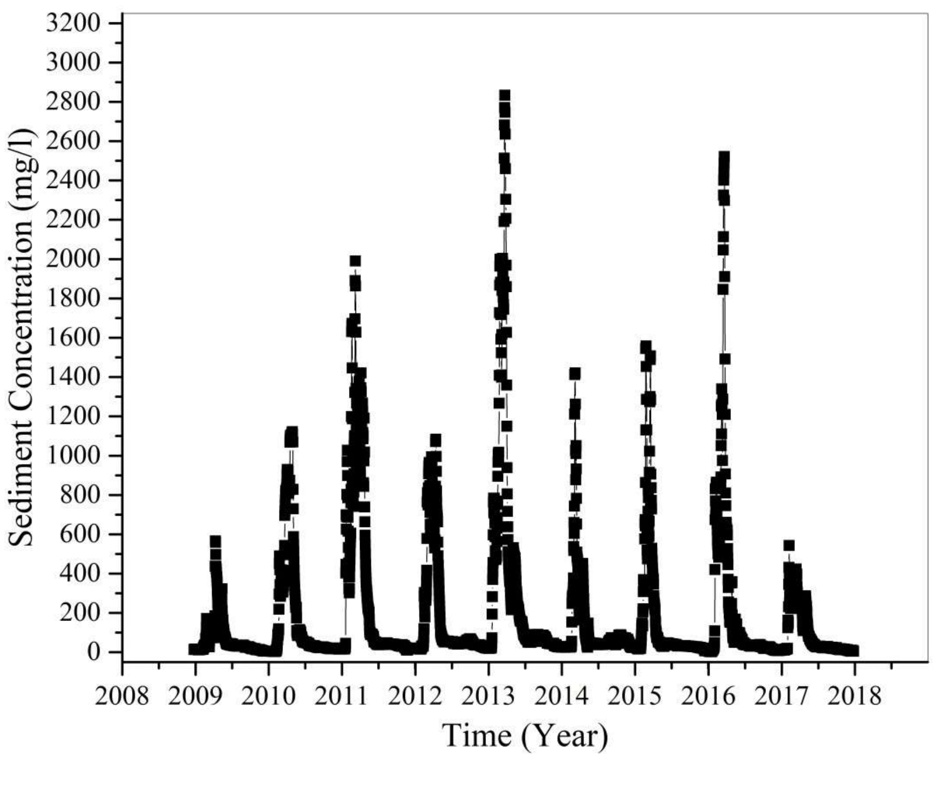

Figure 6.22 sediment concentration at cross-section CS 15

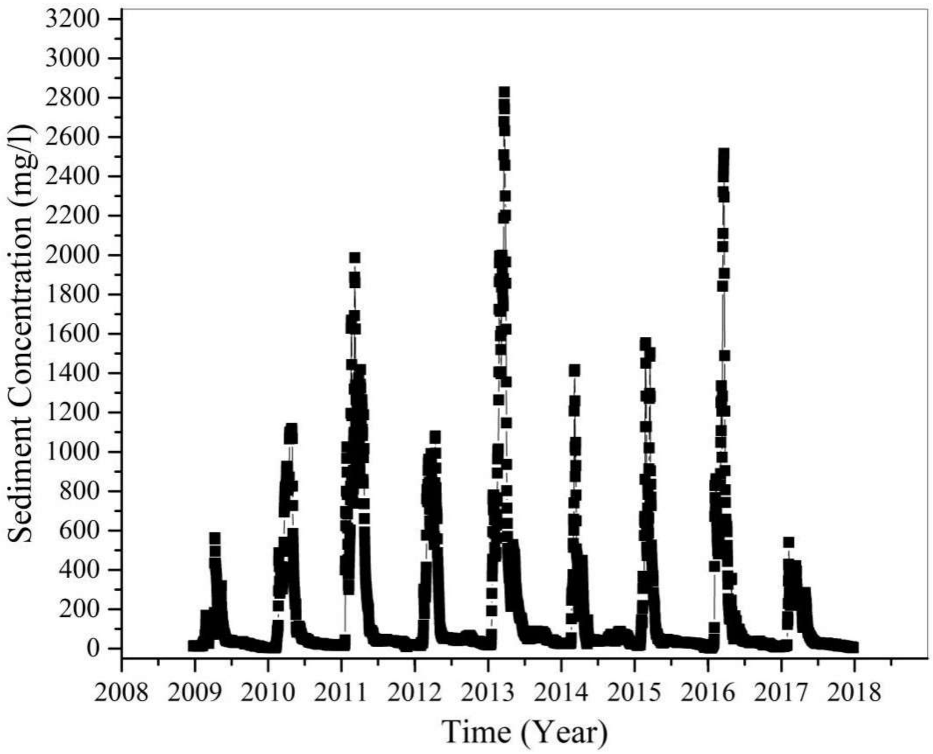

Figure 6.23 sediment concentration at cross-section CS 12

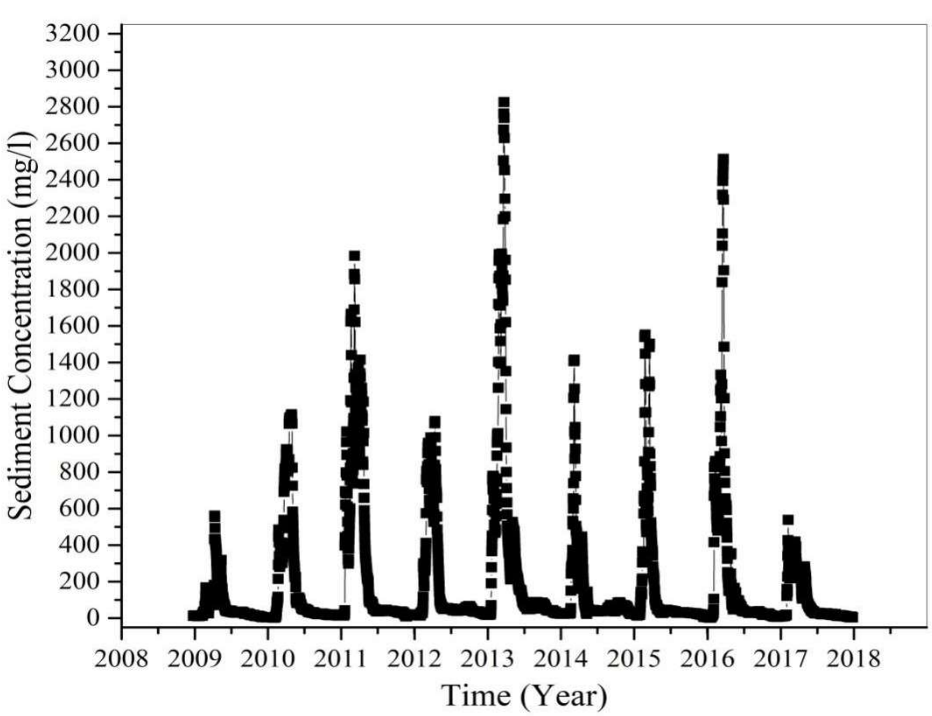

Figure 6.24 sediment concentration at cross-section CS 05

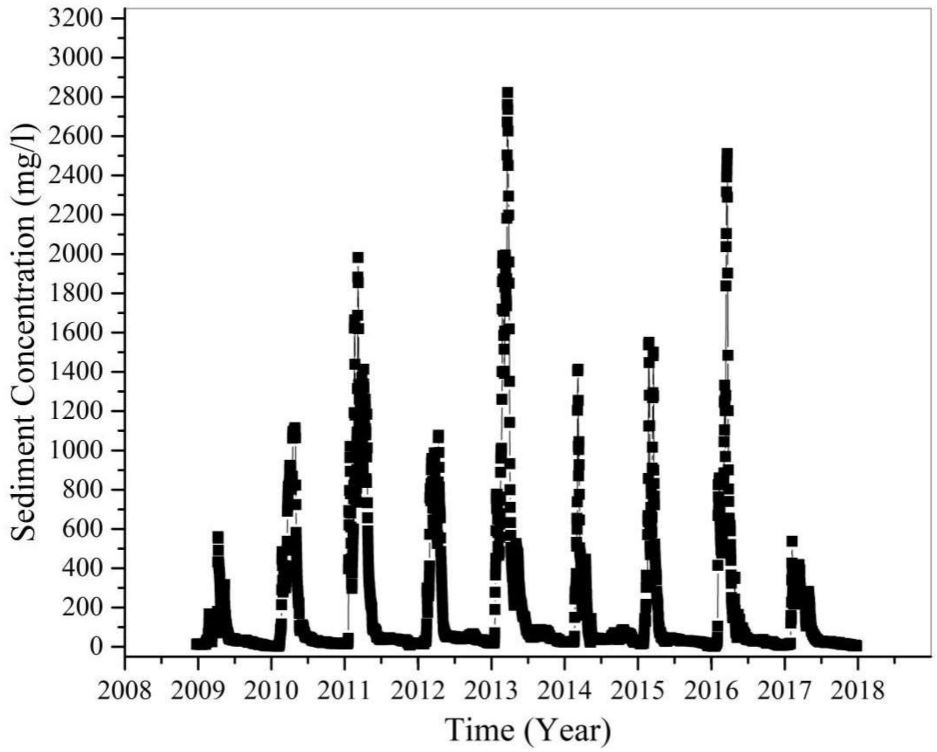

Figure 6.25 Sediment concentration at cross-section CS 02

6.7 VALIDATION OF RESULTS OF SEDIMENT MODEL

Sediment transport modelling was done with the help of HEC-RAS, and results were obtained for different cross-section. During the modelling, process-specific steps and a set of input data are entered. Validation is an essential step for confirmation of the correctness of the process and input data used. For this purpose comparison of the results obtained from the HEC-RAS with the results obtained from the direct measurement is done.

The comparison of the results obtained from the HEC-RAS and direct measurement is made in Figure 6.26 and 6.27. Figure 6.26 shows the sediment concentration obtained from HEC-RAS and direct measurement. It can be observed that HEC-RAS gives a satisfactory result. Also, Figure 6.27 shows the result of the bed profile obtained from HEC-RAS and direct measurement. By comparing these results, it can be concluded that HEC-RAS gives a satisfactory outcome of the bed profile.

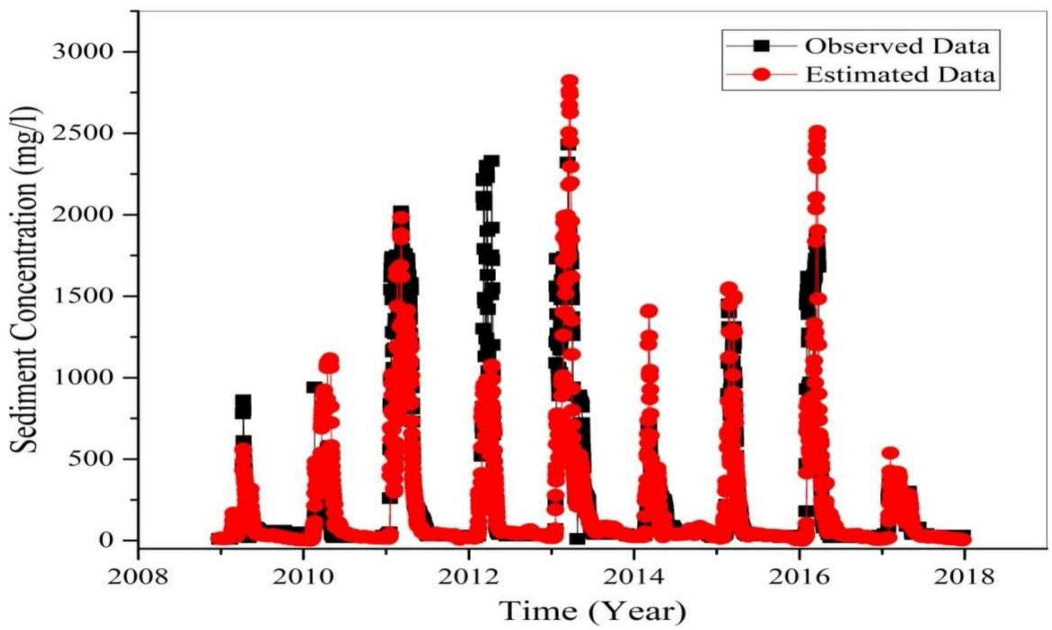

Figure 6.26 Validation of sediment concentration at CS 02 of Varanasi

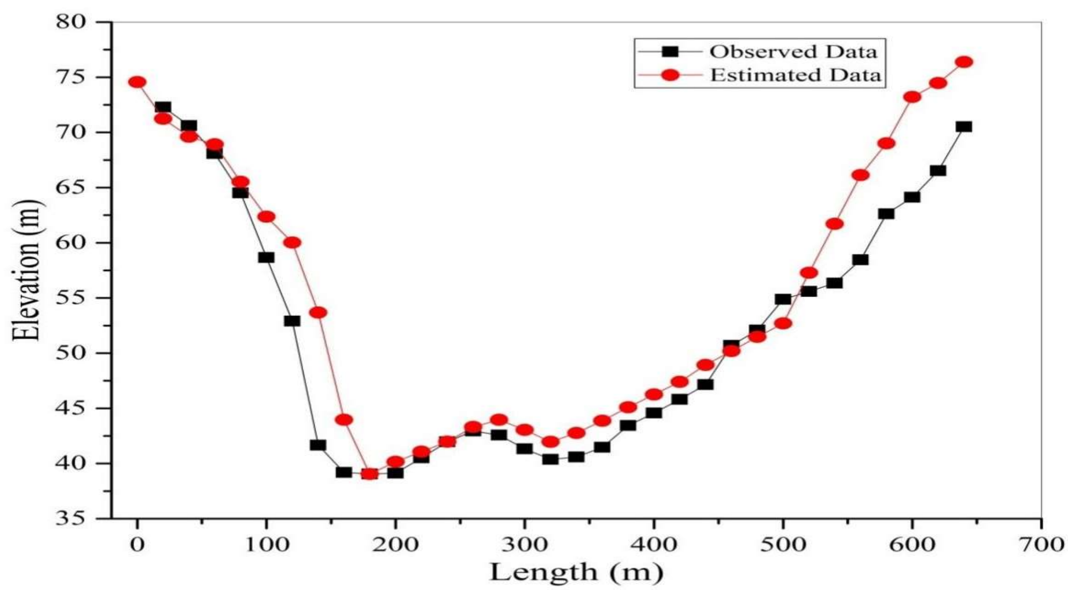

Figure 6.27 Validation of bed profile at CS 02 of Varanasi

6.8 CONCLUSION

Modelling the sediment transport behaviour is essential for predicting sediment concentration and in the prediction of the cross-section of the river. The help of HEC-RAS did sediment transport modelling. During the modelling, a stretch of the Ganga river near Varanasi is considered and divided into fifteen sections. As input data DEM, Metrological data, Hydrological data and sediment data were used. Meyer Peter Muller (MPM) transport function was selected for modelling.

The model developed to estimate the sediment concentration and the cross-sectional profile of the river. Further, the developed model can predict the maximum sediment concentration during the monsoon period when peak flow occurs in the river and the overall erosion in the river bed with time. For validation of the model, the actual measurement was carried out. It is observed that the model matches the precise measurement of the river cross-section. Further, a cross-section near the Raj ghat was critical due to the more significant erosion in both the model and actual measurement. Based upon the predicted and observed value the estimated R^2 and Root mean square error was found 0.92 and 4.2 respectively. The comparison of results has shown that modelling through HEC-RAS can be satisfactorily used to predict sediment transport modelling.