

Simulation of Floods in Delhi Segment of River Yamuna Using HEC-RAS

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Abstract Flooding in Delhi Segment of River Yamuna has a devastating effect on the life of the inhabitants, particularly those residing close to the banks. The River Yamuna experienced floods 33 times during the last century, often endangering the life of people as well as the important infrastructural facilities that exist along the banks of the river. The present paper describes the development and application of a hydrodynamic model based on HEC-RAS – modelling system developed by the Hydrologic Engineering Centre at United States Army Corps of Engineers - for the simulation of floods in the Delhi segment of River Yamuna. The HEC-RAS model was first calibrated and validated and then applied for the simulation of historical floods of 2010 and 2013. With the HEC-RAS model, the vulnerability assessment of different bridges and barrages in the Delhi segment has been carried out. It can be concluded that the results presented herein could provide valuable aid to policy makers in formulating mitigation strategies to counteract the adverse impacts of flooding in the Yamuna River basin.

Keywords: Yamuna, HEC-RAS, flood, mitigation, Delhi

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1. Introduction

Rivers are a significant of irrigation, hydropower, and drinking water supplies. Throughout history, people developed habitats along rivers due to the easy availability of water for a multitude of purposes. But human populations that live on the banks of rivers are significantly vulnerable to flooding in the river. In developing countries such as India, the inhabitants are particularly vulnerable to devastation caused by floods. Another major reason for the huge devastation caused by floods in the developing countries is the deficiency of rapid response infrastructure. The impact of flooding on human life and infrastructure has become more profound in the wake of climate change in the developing countries. Owing to its low elevation, Bangladesh is highly vulnerable to flooding events. More than fifty percent of the land area in Bangladesh is at an elevation of less than 8 m above mean sea level. A major flood that occurred in Bangladesh in 1991 caused huge devastation in the country. More than 200,000 persons were reported to have died due to extreme floods in the country. The extent of inundation in Bangladesh was more than 33 percent during the flood of 1991. The developed nations, on the other hand, are able to manage adverse impacts of flooding in a much better manner than the developing countries, primarily due to the availability of adequate flood control infrastructure. The fury of floods,

however, cannot be avoided despite the flood control measures in place in the developed world, mainly due to the inherent complexities associated with the occurrence of floods.

With the availability of sophisticated forecasting models, it is possible to predict the occurrence of floods to a reasonable extent. Analysis of flood records at a particular location is required for computing the magnitude of various return-level floods at that location. The flood protection measures at a particular location can be planned and designed based upon the likely magnitude of flood at that location. Although it is possible to provide protection against flood to a large extent, but it is not possible to alleviate the problem of flooding completely. Modelling procedures that allow the transformation of discharge to stage at a particular location are an important part of water resources planning and management. With the advent of sophisticated computer programs, it has now become possible to manage floods better than ever before.

Numerous flood modelling studies have been conducted using available software packages. Ahmad [1] applied MIKE 21 to simulate the response of the Red River basin in the USA and Canada. Tate and Maidment [2] presented a methodology based on HEC-RAS for the two- and three-dimensional floodplain mapping using Arc GIS. Husain. A [3] presented a Flood modelling by using HEC-RAS Yang and Rystedt [4] used geographic information systems (GIS) and hydrodynamic modeling to simulate flood events along a river channel in areas near a residential development in Eskilstuna community, Sweden.

Snead [5] presented the application of two unsteady flow hydraulic models, Mike 11 and HEC-RAS for flood routing and visualization for the Mill Creek Watershed located in Cincinnati, Ohio. Zadeh et al. [6] estimated the extent of the flood zone and economic damages over an 8.2 km reach of the perennial LaeenSoo River in the northern Khorasan Province, Iran using HEC-GEORAS, a combination of HEC-RAS and Arc View GIS software. An application of Mike 11 to the simulation of flow in Euphrates River in Iraq has been presented by Kamel [7]. The results of the study demonstrated that the model provides a good simulation of the observed flows. Pareta [8] developed a model for simulating flood inundation boundaries. With the model developed by Pareta [8], it was possible to precisely overview the extent of flooding in the area of interest. Sharif et al. [9] investigated trends in magnitude and timings of flows in the Upper Indus basin – a climatically sensitive basin in the Himalayan region. Trends in several hydro-meteorological variables were investigated by Khattak et al. [10] in the upper Indus River basin (UIRB).

An analysis of flow dynamic process and the quantification of the peak discharges by using HEC-RAS has been presented by Villazón et al. [11] for the Piraf River. The authors simulated unsteady flows using derived hydrographs from measured hourly water levels as boundary conditions. Al-Fahdawi [12] applied a numerical model to hydrodynamic modelling of the Euphrates River in its reach between Haditha Dam and Hit city. The author used HEC-RAS model to determine different parameters from a given flood caused by a hypothetical foundation failure of Haditha Dam. Yarrakula et al. [13] developed a flood forecasting model for the Subrnarekha River. The digital elevation Model (DEM) of the study area was prepared using the high resolution CARTOSAT-1 imageries. Cecile Ashwanden et al. [14] compared water surface profiles for Tar River generated from steady and unsteady flow hydraulic models. Brych et al. [15] used HEC-RAS to prepare flood inundation maps for the Orlice valley in the Czech Republic. Extreme floods were considered to calibrate the hydraulic model of the Orlice river system. Khattak et al. [16] describes the application of HEC-RAS model for the development of floodplain maps for the part of Kabul River that lies in Pakistan.

Several flood modelling studies have been carried out in Indian basins over the last decade. Vijay et al. [17] describes a hydrodynamic model called River CAD for the assessment of extent of inundation, and evaluation of different development scenarios in the basin of interest. Mazumder [18] describes a methodology for the determination of waterway for a bridge using detailed topographic, hydrologic, and morphological investigations. Pramanik et al., [19] used extracted river cross-sections to simulate the magnitude of flood in the deltaic reaches of Brahmani river basin located in the eastern India. Timbadiya et al. [20] developed an integrated hydrodynamic model of the lower Tapi River, India. Firstly, the one-dimensional hydrodynamic model was calibrated for Manning's roughness of river channel and, subsequently one-dimensional and two-dimensional integrated hydrodynamic model was used to ascertain the sensitivity of Manning's 'n' on coastal flood plain depth of the lower Tapi River. Doiphode and Ravindra [21] focused on the concepts of

hydraulic flood routing model, with time-varying roughness updating to simulate flows through natural channels. The authors solved Saint Venant's equation using the quasi-steady dynamic wave and full dynamic wave theory. A case study of unsteady flood modelling through HEC-RAS was carried out for the Karad - Kurundwad reach of the Krishna River. Sankhua et al. [22] focused on the concepts of hydraulic flood routing model, with time-varying roughness updating to simulate flows through natural channels, based on the quasi-steady dynamic wave and full dynamic wave theory, emphasizing the solving of the intricate Saint Venant's equation. Several studies have been carried out in Yamuna River basin as well. For example, Sharma et al. [23] focused on the monitoring of the diffuse pollution characteristics of the agricultural land confining the River Yamuna in Delhi. Vijay et al. [24] presented hydrodynamic simulation of the river Yamuna under different designated flood flows to delineate the land availability under existing and modified riverbed geometry including channel dredging and riverbed dressing. Kumar et al. [25] describes flood management strategies for the national capital region of Delhi, India. Husain. A [26] describe the method flood peak estimation at Hathinkund and Okhla barrage at Yamuna River for the national capital region of Delhi, India. An application of POT approach for estimation of floods of varying return periods has been described by Kumar et al. [27]. The major objective of the present research is to develop a hydrodynamic model for the simulation of floods in the Delhi segment of River Yamuna. The intent is to assess the vulnerability of hydraulic structures in the Delhi segment of River Yamuna to floods associated with different return-levels.

2. Study Area

River Yamuna is one of the major rivers of India and the largest tributary of the Ganga. The river originates from the Yamunotri glacier of the lower Himalayas at an elevation of 6320 m above mean sea level (Figure 1). The river has a total length of 1376 km and drains an area of 345848 km². In the upper reaches of River Yamuna, there are several hill streams that join together to form the main stream. There are four main rivers that join Yamuna in the high Himalayan ranges. These include Rishi Ganga, which joins on the right bank of the Yamuna, whereas the Hanuman Ganga joins on the left bank. In the lower Himalayan ranges, the Yamuna River receives Kamal, Tons, Giri and Beta on its right bank and Aglag and Asan on left banks. The Chambal, Betwa, Sindh and Ken are the important tributaries joining Yamuna on the right bank in the plains. The Hindon river joins River Yamuna on its left bank. Among all these tributaries, Tons at hills and Chambal at plains are the most important tributaries in terms of their discharges. The Tons is the principal source of water in mountainous range and generally carries more water than the main stream. In plains, during non-monsoon period, River Chambal contributes about 5-10 times more water to the Yamuna than its own flow. However, since the year 2003, there is a significant reduction in the water quantity that River Chambal discharges into the Yamuna River.

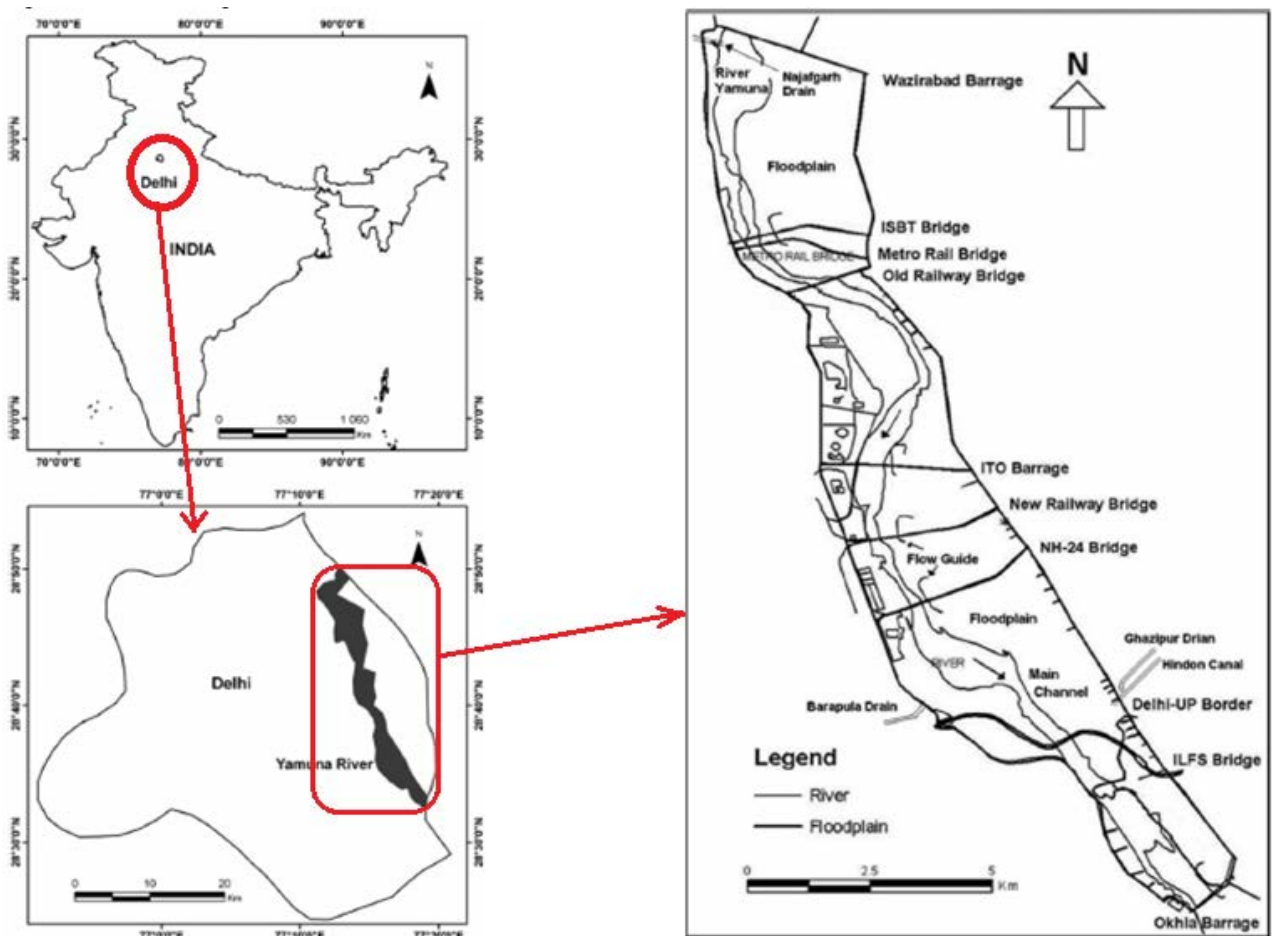


Figure 1. Schematic of Delhi Segment of River Yamuna

There are five barrages that control the flow of Yamuna waters during its journey from the Himalayas to the National Capital Territory of Delhi (NCT). These barrages are located at Dak Patthar (about 160 km from origin in Uttaranchal), Hathnikund (172 km distance from origin, just at foothills in Haryana), Wazirabad (in NCT of Delhi, 396 km distance from origin), Okhla (in NCT – Delhi, 418 km distance from origin), and at Mathura (Near Gokul village in Uttar Pradesh about 570 km distance from origin). These barrages are the major water abstraction locations on the river. The water is contributed into the Yamuna River, not only through its tributaries, but also by the canals and drains originating from various urban centers.

The three major cities - Delhi (the capital of India), Agra (the city known for Taj Mahal) and Mathura (the birthplace of Lord Krishna) are situated on the banks of River Yamuna. The Delhi stretch of the river Yamuna from Wazirabad barrage to Okhla barrage is around 23 km long, and is located between $28^{\circ} 28' 05''$ – $28^{\circ} 54' 36''$ N and $77^{\circ} 09'$ – $77^{\circ} 24'$ E at the downstream. The Yamuna enters in the National Capital Region (NCR) of Delhi, approximately 1.65 Km north of Palla Village. It runs for about 45 kms in the southeast direction before leaving NCR of Delhi at a point to the east of Jaitpur downstream of Okhla Barrage. The total area of the river in the Delhi stretch is about 9,700 ha of which 1,600 ha of land is under water (river extent) and the remaining 8,100 ha is dry land (floodplains). Three barrages namely Wazirabad barrage, Yamuna/ITO barrage and Okhla barrage are

found within the highly braided river stretch. These barrages are operated only during the monsoon period, when excess of water leads to flooding in the adjoining areas. The total discharge at Tajewala (now Hathnikund) often exceeds 500,000 cusec during the monsoon peak flows, and the Hathnikund Barrage itself has been designed for a 100-yr peak discharge of 776,900 cusec (22,000 cumec). On the other hand, the flow during the summer decreases to only a few thousand cusec [28].

3. Data

In the present work, simulation of water surface profile at different locations of interest has been carried out using HEC-RAS. Two main types of data, namely the geometric data, and hydraulic data, are required for the hydraulic analysis of the stream channel geometry. These data along with the flow data have been used in this research. The basic geometric data include establishing the connectivity of the river system (river network); cross sections; reach lengths, and hydraulic structures such as bridge piers. The River Schematic in HEC-RAS allows to define river network and reference cross-sections and control structures in the river as well as to graphically obtain an overview of model information in the current simulation. The river system schematic should be developed before any other data can be entered. The river centerline of the study area contains x- and y-coordinate data in a 2-D

plane so as to spatially connect the unsteady flow models to the corresponding terrain models. The model automatically looks for a companion file to the image. This file contains information about the image, including the coordinate system and the extents of the image. Figure 2 shows the River system schematic for the study reach.

3.1. Geometric Data

The geometric data can be created either by using Geo-RAS or through manual entry of the cross-section

data. For the manual entry of the data, the details of 77 cross-sections along the study reach of 23 km between Wazirabad and Okhla Barrage was obtained from the Irrigation and Flood Control Department of the government of the National Capital Territory of Delhi. A typical cross section at Old Railway Bridge is shown in Figure 3. Using the data from the DEM, the geometric data for the study reach can be created using HEC- GeoRAS extension of ArcGIS. A typical cross section at Old Railway Bridge is shown in Figure 3.

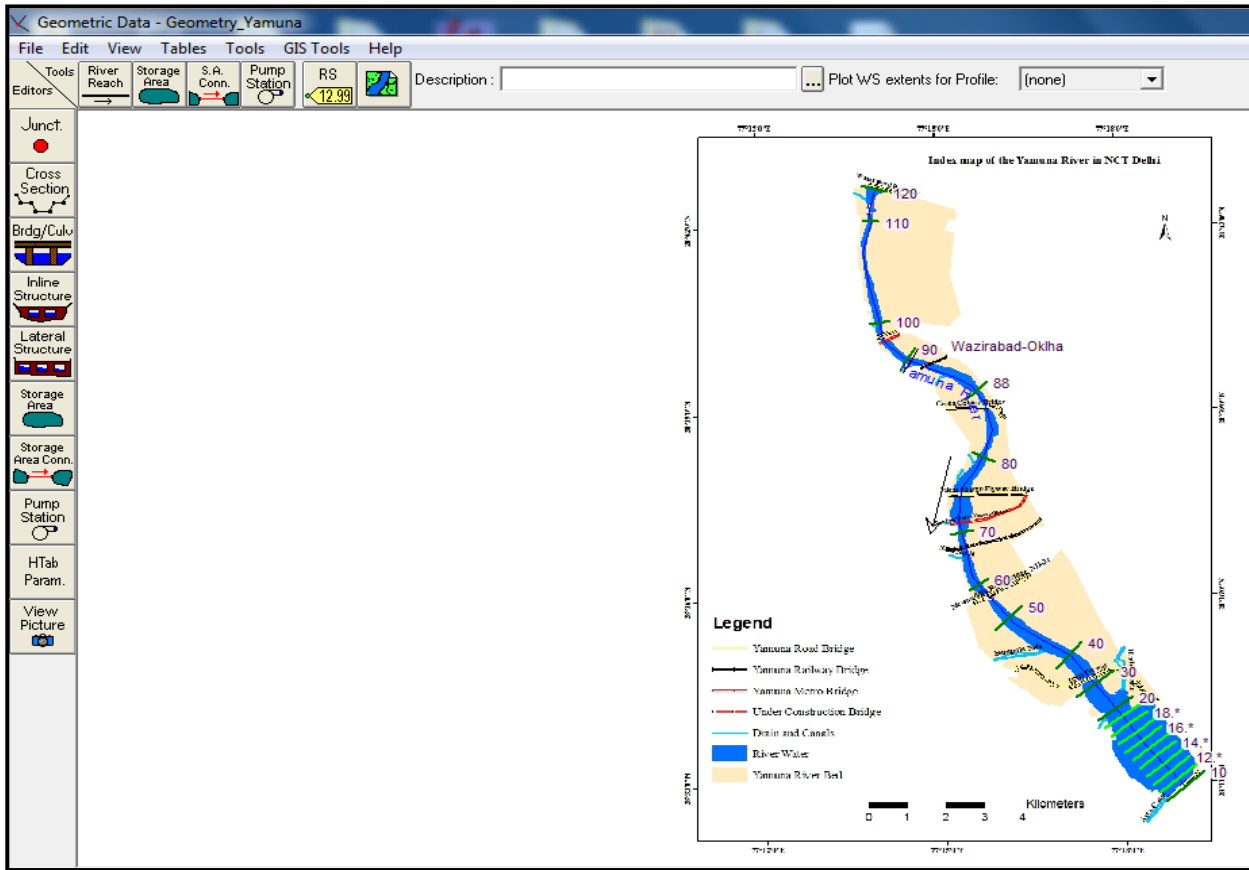


Figure 2. River system schematic for the study area

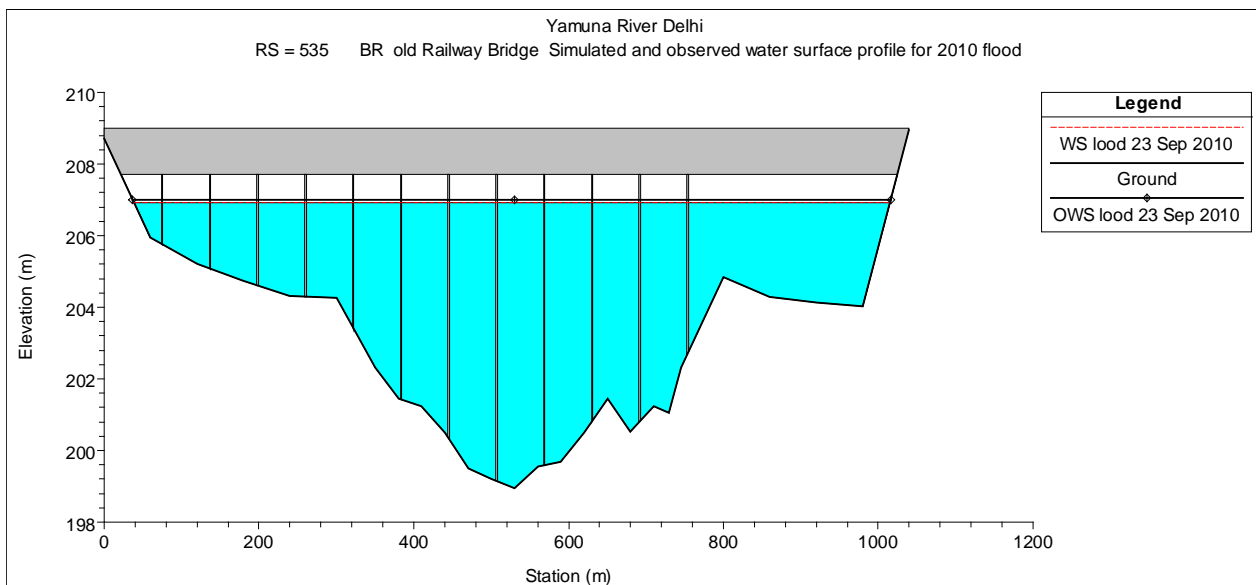


Figure 3. Cross sections of Yamuna River at section u/s of Old Railway Bridge

3.2. Hydraulic Data

Unsteady flow model requires, at least two forms of hydraulic data, namely energy loss coefficients and unsteady flow data. In this study, two types of loss coefficients are utilized by the numerical model to evaluate energy losses; (1) Manning coefficient values or equivalent roughness “k” values for friction loss, and (2) contraction and expansion coefficients to evaluate transition losses, and bridge loss coefficients to evaluate losses related to weir shape, pier configuration, pressure flow, and entrance and exit conditions. The minimum and maximum values of Manning’s coefficient, derived from test studies, for different materials have been presented by Prasuhn [29]. Where the change in river cross section is small, and the flow is subcritical, coefficients of contraction and expansion are typically of the order of 0.1 and 0.3, respectively. When the change in the effective cross-section area is abrupt such as at bridges, contraction and expansion coefficients of 0.3 and 0.5 are often used. Typical values for contraction and expansion coefficients, for subcritical flow are available in Hydrologic Engineering Center (RD-42) [30].

4. Methodology

The HEC-RAS modeling system [31] developed by the Hydrologic Engineering Center at the US Army Corps of Engineers was used to simulate one-dimensional flow through the Delhi segment of River Yamuna. The dynamic routing model in HEC-RAS is based on the dynamic wave theory of the Saint-Venant equations which consist of the continuity and momentum equations. HEC-RAS uses a semi implicit scheme, which is a combination of implicit and explicit finite difference scheme, to solve these equations. Main inputs to the model include flow regime, starting elevation, discharge, loss coefficient, cross-section geometry and reach length for both the main channel and the floodplain. The model can handle bridges, weir flow, meander in streams and split flow options. The computational procedure is based

on the solution of the one-dimensional energy and momentum equations using the standard step method.

The model was calibrated by adjusting the hydraulic parameters. The *theta* (implicit weighing factor) value was varied from 0.6 to 1. Repeated simulations were conducted after modifying the number of iterations and the value of Manning’s roughness coefficient. The discharge data at Okhla Barrage, ITO Barrage Old Railway Bridge and Wazirabad Barrage for the period 09-07-2010 to 06-10-2010 was taken for the calibration and validation purposes. The cross section data are available for 77 stations within the study reach between the Wazirabad Barrage and Okhla Barrage. The available data were divided into two parts; the first part of the data spanning from 01-09-2010 to 27-09-2010 was used for the calibration, whereas the second part of the data spanning from 01-08-2010 to 31-08-2010 was used for the validation purpose.

5. Results and Discussion

Once the model was calibrated and validated, the model was executed to simulate 2010 and 2013 flood in Delhi. For each case, the output from simulations was produced in both graphical as well as tabular format. The output contains the rating curves, water surface profiles, and hydrographs and XYZ perspective plots, and is available for all the cross sections.

Case 1: 2010 Flood

The observed water levels during the 2010 flood were available at four locations in the study reach, namely Wazirabad Barrage, Old Railway Bridge, ITO Barrage and Okhla Barrage. The calibrated and validated HEC-RAS model was used to simulate water levels at different locations in the study reach. A comparison of simulated water levels with the observed water levels was carried out. Figure 4 shows the simulated and observed water levels at different locations in the study reach. The values of simulated and observed water surface elevations as well as the difference between the observed and the simulated water levels for four locations in the study reach are shown in Table 1.

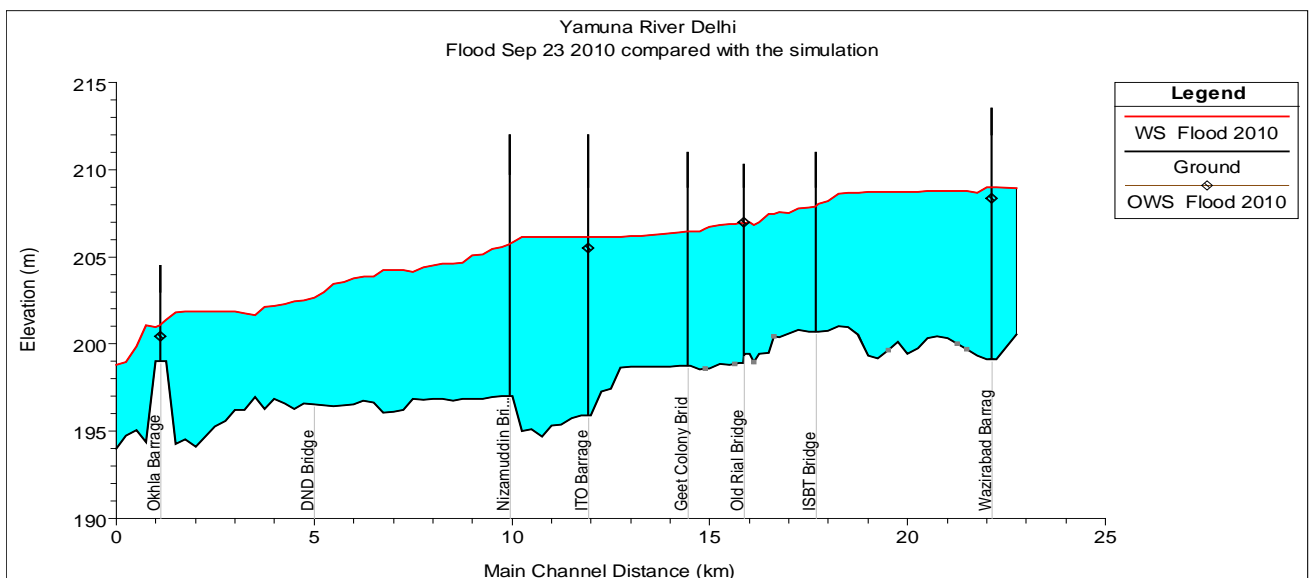


Figure 4. Simulated and observed water surface profile for 2010 flood

Table 1. Output of HEC-RAS simulations for the 2010 flood

River Station (Number)	Water Surface Elevation (m)		
	Simulated	Observed	Observed-Simulated
Wazirabad Barrage (775)	208.98	208.35	-0.63
Old Railway Bridge (535)	206.96	207.0	0.04
ITO Barrage (395)	206.16	205.5	-0.66
Okhla Barrage (2)	201.38	200.45	-0.93

It can be clearly seen from Table 1 that the difference between the observed and simulated water levels is negligible at Old Railway Bridge. At the other three locations, namely Wazirabad Barrage, ITO Barrage and Okhla Barrage the simulated water levels were found to be slightly higher than the observed levels. Thus, it may be concluded that the model tends to overestimate the water levels at some locations, although the magnitude of overestimation is not significantly high.

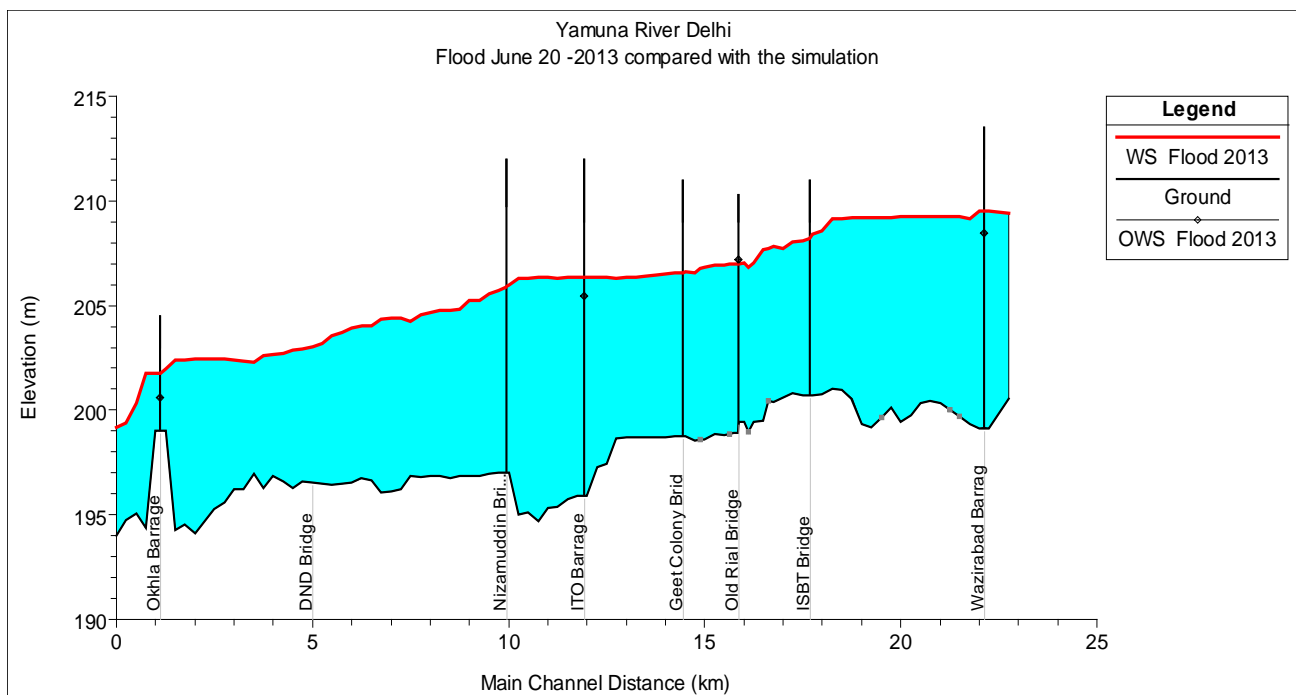
Case 2: 2013 Flood

The HEC-RAS model was used to simulate 2013 flood.

Figure 5 shows the simulated and observed water levels for the 2013 flood. The simulated water surface profile is shown in red, whereas the dots indicate the observed water levels on 19 June 2013. The numerical values of simulated water levels are shown in Table 2. It can be seen from Table 2 that the difference between the simulated and observed water levels is negligible at the Old Railway Bridge, whereas there was some overestimation of water levels at the other three stations. However, the amount of overestimation is not significantly high.

Table 2. Observed and HEC-RAS simulated water levels under 2013 flood

River Station (Number)	Water Surface Elevation (m)		
	Simulated	Observed	Observed-simulated
Wazirabad Barrage (775)	209.21	208.45	-0.76
Old Railway Bridge (535)	207.04	207.18	0.14
ITO Barrage (395)	206.23	205.5	-0.73
Okhla Barrage (2)	201.52	200.6	-0.92

**Figure 5.** Simulated and observed water surface profile for 2013 flood

6. Conclusions

Since the overarching aim of the present research was to conduct an assessment of the vulnerability of different hydraulic structures in the reach of River Yamuna between Wazirabad Barrage and Okhla Barrage, the HEC-RAS model was used to simulate water surface profiles in the study reach. The HEC-RAS model was first calibrated and validated and then applied for the simulation of water surface profiles under 2010 and 2013 floods. The output from the HES-RAS model was utilized to determine the extent of overtopping of bridges/barrages in the study reach when subjected to flood of a given magnitude. Comparison of the observed water levels with those simulated by the HEC-RAS model for the 2010 flood indicated a near perfect match at the Old Railway Bridge. For the other three locations, namely Wazirabad Barrage,

ITO Barrage and Okhla Barrage, the difference between the observed and the simulated water levels were found to be insignificant under 2010 floods. At these three barrages, the model slightly overestimated the water levels. For the 2013 flood as well, the model simulated water levels that were in close agreement with the observed levels.

A HEC-RAS model has been developed for simulating water surface profiles under a given set of flows at different locations in the study reach. With a well calibrated and validated model, the vulnerability of hydraulic structures in the study reach can be easily assessed, and if required remedial measures can be taken. With the model developed herein, the vulnerability of the Yamuna basin to flooding events can be evaluated under floods of any given magnitude. The modelling process in the present research was confined to the study reach between Wazirabad and Okhla Barrage. The future studies shall consider expanding the study area

by increasing the nodes in the network currently considered in the modelling process. For greater reliability in the assessment of vulnerability of bridges/barrages under inputs to HEC-RAS from a larger number of RCMs, rather than a single model should be utilized. Depending upon the availability of the data, the future studies would employ a larger ensemble of RCMs and development scenarios for understanding the range of climate change impacts on the hydrologic regime in the Yamuna River basin. Information related to streamflow projections could be incorporated into planning activities. The model developed herein could be applied to simulate future floods in the basin, and therefore aid in the development of strategies for mitigating the adverse impacts of floods in the basin.

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