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Hydrodynamic Simulation of River Yamuna for Riverbed Assessment: A Case Study of Delhi Region

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Abstract A well known river hydrodynamic model RiverCAD has been used to simulate and visualize flood scenarios for different designated flood flows under complex riverbed geometry with several man made structures like bridges and barrages. The model applied successfully for the stretch of 23 km in the Yamuna floodplain of Delhi region from Wazirabad barrage in the upstream to Okhla barrage. Flood flows for various return periods namely once in 10, 25, 50 and 100 years were estimated based on recorded flow data for the period of 1963 to 2003 using standard flood frequency analysis techniques. The simulation results were compared and the model was calibrated with water surface elevation records of the previous floods at various barrage and bridge locations. Simulation results enabled prediction of maximum water levels, submergence scenarios and land availability under different designated flood flows for riverbed assessment, development and management.

Keywords Flood · Hydrodynamic · River · Water level · Inundation · RiverCAD

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1 Introduction

River flooding is an important phenomenon for annually inundated floodplains since it supports desilting and enhances biological integrity of aquatic and terrestrial ecosystems. During flood, the temporary structures created, and the activities being carried out get washed off, causing severe damage to human life and other property (Parker, 2000). The reports of floods in different parts of the world for several decades reveal the same scenario of enormous economic damage and human sufferings (Dwarkin, 1976; Glickmen, Godling, & Silverman, 1992; Shah, 1983; Sheehan & Hewitt, 1969). According to Jacobson (1993), "the primary factor that leads to loss of life is the inhabitants lack of perception of the hazard of flash floods."

River margins support ecological balance by the community interaction through land–water interface. However, the encroachment of riverbed for developmental activities is resulting into reduction in river margins and increase in unwanted flows and wasteloads (CWC, 1991, 1996). The unplanned and the unmanaged activities result into water logging, flooding in urban areas, blocking wastewater drains; thus causing loss of property, human life, sufferings, epidemics; and the unauthorized encroachments result into waste generation and environmental degradation in the riverbed (CPCB, 1993, 2000; Trivedi, 1988).

The engineering measures which protect the development form floodplain are construction of dams and reservoirs. However, with increasing environmental concern and decreasing public support for large-scale flood control structures, engineers and hydrologists are concentrating on non-structural approaches to reducing flood damages. These include floodplain regulation by improving the drainage and framing guidelines for floodplain development (Pietroniro, 2005). Both the structural and non-structural approaches to flood mitigation require hydrodynamic simulation for flood flows of various return periods (Lecce, 1997; Spaliviero, 2003). Similar studies on developing simulation models of riverbed for sustainable development of floodplains have been reported in the literature (Nijland, 2005; Parker, 1995; Toni & Sinclair, 2005).

The present study with the objective of Yamuna riverbed assessment has been carried out by hydrodynamic simulation for flood scenarios of various return periods. Hydraulic Engineering Center's River Analysis System (HEC-RAS, 1997), a one-dimensional model for simulation of water surface profiles for steady flow conditions has been used with due consideration to channel geometry, floodplain conditions, structural controls, bed roughness and peak discharge conditions. The peak discharges were estimated based on flood frequency analysis (Punmia & Pande, 1990; Subramanya, 1997) of historic stream flows at a specified river location of old railway bridge recorded by Central Water Commission, India. The water surface profiles were simulated for potential floods of once in 10, 25, 50 and 100 years return periods. The submergence scenarios and corresponding land availability have been obtained by overlaying the model simulations of water surface profiles on river topography using Surfer (Golden Software, 1996).

2 Study Area

The Yamuna river stretch is around 23 km from Wazirabad barrage in the upstream to Okhla barrage in the downstream as shown in Figure 1. The study area lies between 28° 28′ 05″–28° 54′ 36″ N and 77° 09′–77° 24′ E (Toposheet No. 53H, SOI) having an area about 4,480 ha. The riverbed is 2 to 3 km wide whereas waterway in the stretch is confined to a width of 450–800 m during the non-monsoon period. The river meanders at places and large areas of riverbed are lying vacant. The predominant landuse activity in the riverbed is agriculture. The other activities leading to pollution and environmental damages in the riverbed are encroachments, power station, fly ash dump, cremation ground, bathing ghats, sanitary landfills, water works and sewage treatment plants.

The climate of Delhi is extreme in both summer and winter with temperature variation from 44.2 °C to 27.6 °C and 22.2 °C to 3.5 °C respectively. Relative humidity is minimum in dry weather months and maximum during monsoon months. The mean annual rainfall of the region is about 714 mm (Bhaskar, 1998; Pandit, 1998). The hydrogeology of the area is governed by two distinct types of aquifer namely quartzite rock and alluvial aquifer. Groundwater occurs under water table and confined to semi-confined conditions in both the formations. Over the last few decades the water quality in the river has deteriorated due to increased wastewater discharges from major storm water drains and growing encroach-

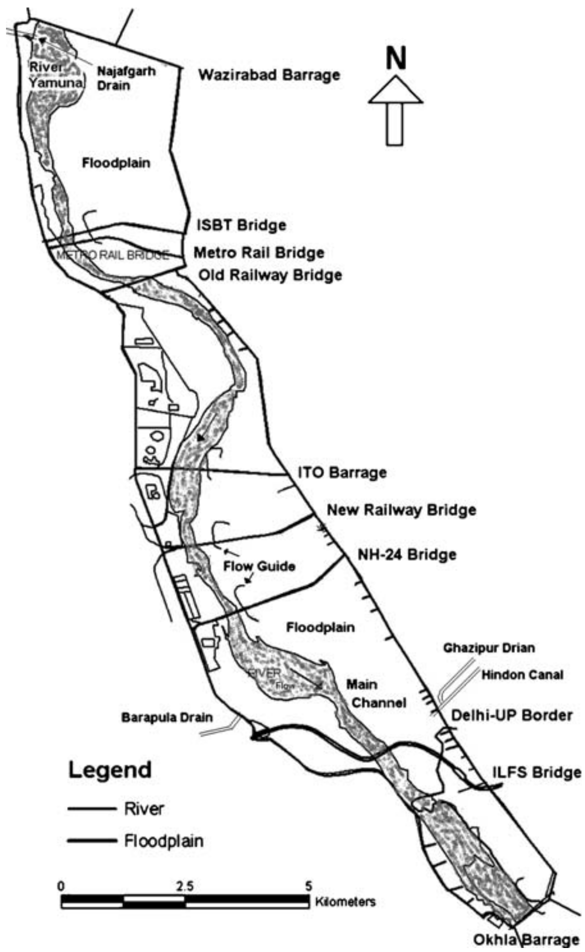

Figure 1 Index map of the Yamuna river floodplain in NCT Delhi.

ment in the riverbed (CBPCWP, 1982). Najafgarh, supplementary and Barapula drains are shown in Figure 1 contribute more than 90% of the wastewater in to river Yamuna.

3 Methodology

3.1 Flood frequency analysis

For estimation of water surface profiles and inundation scenarios under different flood flows conditions, specific discharges were obtained by flood frequency analysis of the flood records for the period between 1963 to 2003. All the commonly used frequency distribution functions for prediction of extreme flood values namely Gumbel's extreme value distribution (Ang & Tang, 1984; Gumbel, 1958), Log-Pearson Type II distribution (IACWD, 1982) and Log-normal distribution (Hoshi, Stedinger, & Burges, 1984; Stedinger, 1980) were employed and compared. Gumbel's method, which is one of the most widely preferred and suitable for statistical distribution used for frequency analysis. Flood flows for 10, 25, 50 and 100 years return periods were estimated and presented in Table I.

3.2 Mathematical model

The RiverCAD model a highly optimized version of HEC-RAS has been used for the hydrodynamic simulation of river Yamuna. The model simulates water surface profiles for steady gradually varied flow under sub-critical flow regime conditions taking into account the effects of various obstructions such as bridges, culverts, weirs & structures.

Table I Various return flood flows of Yamuna at old railway bridge

Return period	Flood flow (Cumecs)
1 in 10 years	5,629
1 in 25 years	7,034
1 in 50 years	8,077
1 in 100 years	9,111

The energy equation used to determine the water surface elevation is written as follows:

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e$$

where

- WS_1, WS_2 water surface elevations at reach ends
- V_1, V_2 mean velocities (total discharge/total flow area) at reach ends
- α_1,α_2 velocity coefficients for flow at reach ends
- g gravitational acceleration
- h_e energy head loss

The energy head loss (h_e) between two cross-sections is comprised of friction losses and contraction or expansion losses. The equation for the energy head loss is written as

$$h_e = L\overline{S}_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right|$$

where

- L discharge-weighted reach length
- S_f representative friction slope for reach
- C expansion or contraction loss coefficient

The water surface profiles are computed from one cross section to the next by solving the energy equation with an iterative procedure called the standard step method (Boss, 2000). The computations begin at one end of a study reach and proceed section by section to the other end of the reach (Choudhry, 1993; Chow, 1959). At bridge crossings where, the flow hydraulics is more complicated, momentum and other equations are used to compute the water surface elevation changes. Input data for simulation includes starting water surface elevation, discharge, cross-sectional geometry and reach lengths, Manning's n values and energy loss coefficients, and characteristics of bridges and weirs (Chow, Daidment, & Mays, 1988; Davidian, 1984).

4 Model Application

The model was applied successfully over the river stretch considering all input data including flood discharges given in Table I and corresponding initial

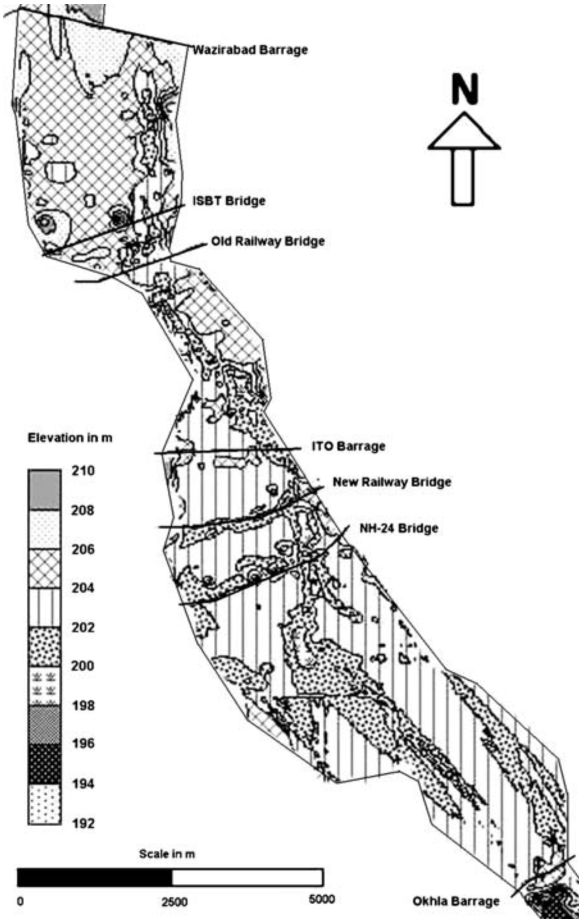

Figure 2 Digital elevation model (DEM) of the riverbed Yamuna.

water levels at most downstream cross section at Okhla barrage obtained from the gauge records. The details of ground topography and roughness and bridge data considered in simulation are presented below.

4.1 Ground topography

The ground topography is defined by the elevations along each cross section from left bund (floodplain boundary) to the right bund including bund elevation. A contour map was prepared using the ground survey data of 101 cross sections measured at intervals 200–300 m along the river. The ground elevation was in the range 194–208 m above mean sea level. The slope of the terrain of most the areas in the study stretch is 0–0.5%. The digital elevation model (DEM) of the river geometry prepared from contour map using Surfer software is depicted in Figure 2.

4.2 Roughness and bridge data

The Manning's coefficient '*n*' varies at various cross sections depending on the resistance to flow due to type and amount of vegetation, channel configuration, etc. The values ranging in between 0.02 to 0.1 have been adopted for various stretches including main river channel, left and right banks and near the bridges (Danniel, 1997; Mays, 2001). There are seven barrages/bridges in the river stretch that have been considered in the simulation. The total loss coefficient

Figure 3 Simulated water surface profiles for various return period floods.

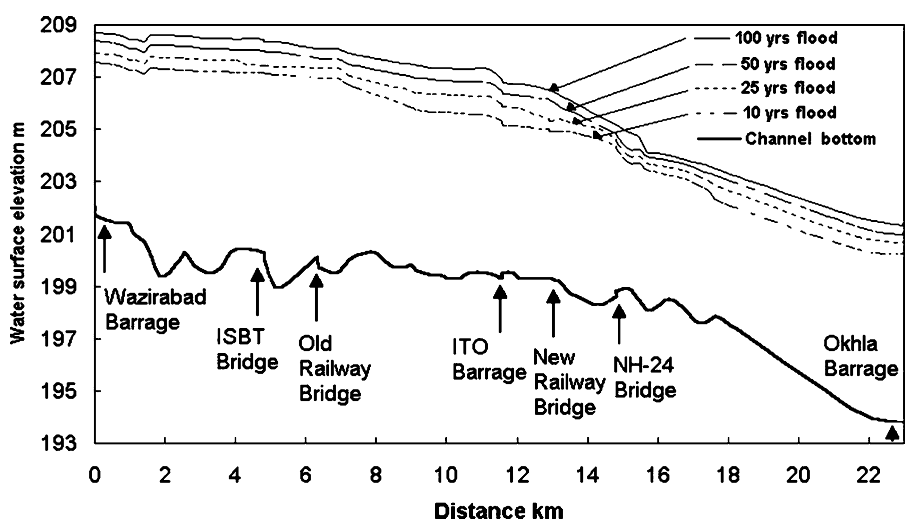

Figure 4 Comparison of observed and simulated water levels.

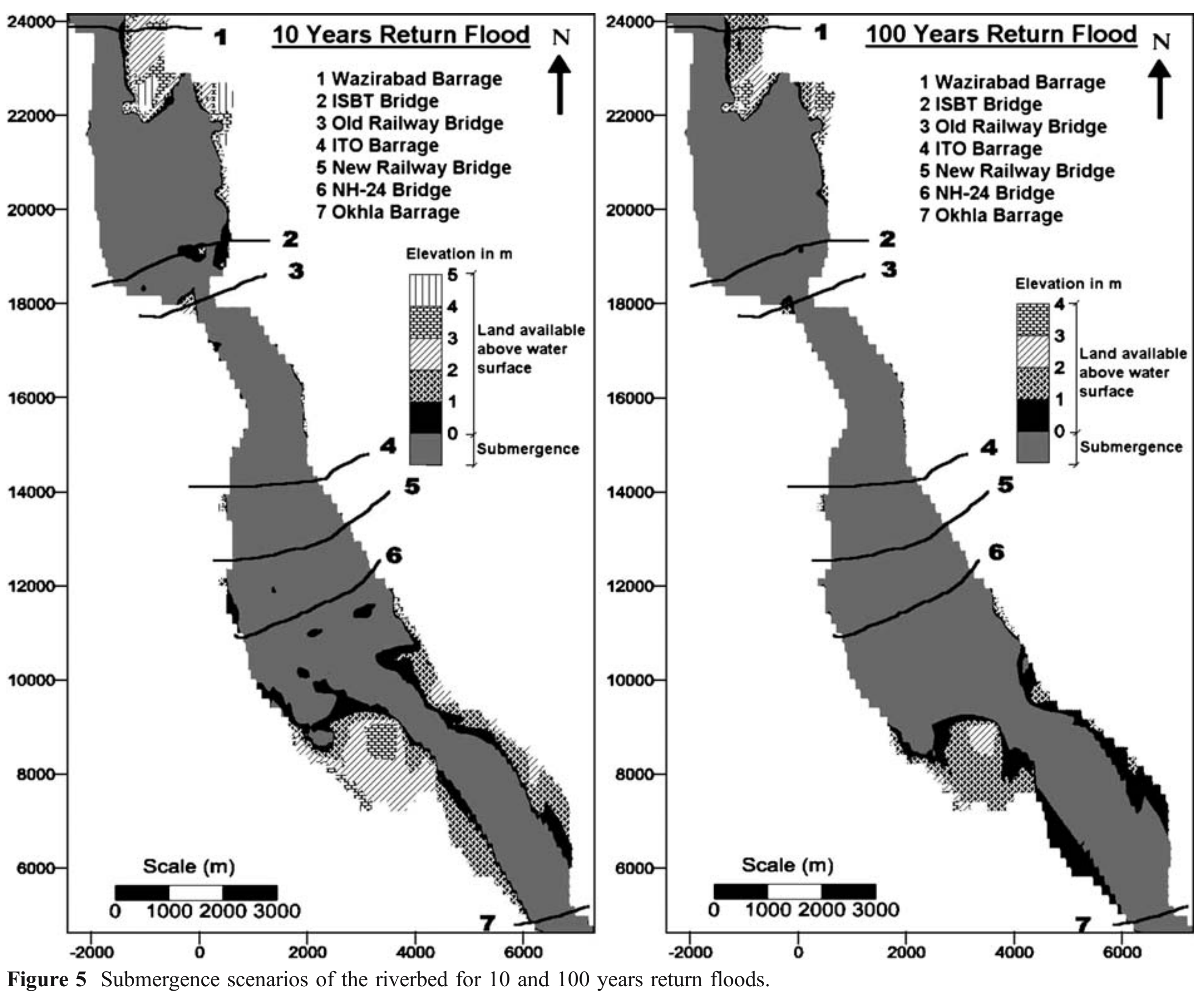

Figure 5 Submergence scenarios of the riverbed for 10 and 100 years return floods.

Table II Land free from submergence

Return period	Land availability (ha)
1 in 10 years	1,147.6
1 in 25 years	989.7
1 in 50 years	873.1
1 in 100 years	762.6

has been taken at bridge cross-sections and suitable values were fixed based on the head available.

5 Results and Discussion

To visualize the impact of designated major floods, simulations were carried out for once in 10, 25, 50 and 100 years return floods. Figure 3 presents the simulated water surface profiles along the river stretch over different cross sections of the riverbed. The changes in water surface profiles can be visualized at barrages and bridge locations. The sensitivity analysis for initial water surface elevation considered different Manning's 'n' for main channel and overbank regions. The Manning's values for left and right overbanks considering vegetation, pasture land with high and short grass ranged from 0.02 to 0.05, whereas, that for main channel with irregular and rough sections ranged from 0.035 to 0.1.

The simulated results were analyzed and compared with observed water levels for flood flows 7,142, 7,027.5, 6,364.7 and 6,744 cumec at Wazirabad, Old Railway Bridge, ITO Barrage and Okhla Barrage, respectively. The 25-year return flow of 7,034 cumec (Table I) being comparable with these flow values, a comparison made for simulated and observed water levels at these stations is presented in Figure 4. The model simulations were considered acceptable in view of close fit of the observed and simulated data except at Old Railway Bridge. The correlation coefficient between observed and simulated water levels was found to be 0.748, which is considered as good.

The calibrated model was used to delineate the inundation and land availability for different flood flow conditions using Surfer software. The inundation due to flood at various locations was considered as the difference between ground and water surface elevation. The inundation obtained was termed as submergence scenarios. Thus the submergence and land area were demarcated by values below zero and above zero, respectively. Figure 5 shows the submergence scenarios and land available above the water surface for once in 10 and 100 year return flood. The estimated area of land free from submergence for once in 10, 25, 50 and 100 years return flood was found to be 1147.6 ha, 989.7 ha, 873.1 ha and 762.6 ha, respectively (Table II). This entire submergence shows the non-uniform spread of water over the river stretch due to lesser depth of river at various sections.

6 Conclusions

The hydrodynamic simulation for river Yamuna presented in this paper provides the flood levels and land availability at various cross-sections in order to assess the inundation and evaluate the possibilities for riverbed development. The simulations for water surface profiles indicated sudden drop in water levels at bridge locations due to smaller opening compared to the river width.

The land availability in case of once in 10 years flood is maximum and that for once in 100 years is minimum as expected. The unauthorized encroachment on the parcels of land in various stretches of the riverbed is one of the major causes for change in the river course with reduction in river width. Such unplanned activities in the riverbed need preventive measures and warning alerts in case of higher flood flows to avoid the flood hazards. Under such situation, the protection of urban area due to flooding of the overbanks is warranted by increasing the height of bunds at some places.

In order to avoid the environmental damages due to flood and other activities, the land availability delineated by floodplain mapping in the riverbed Yamuna from Wazirabad to Okhla may be put to developmental planning. For this purpose, similar hydrodynamic simulation studies would be undertaken with options of river channelisation and riverbed dressing for reduction in submergence. The riverbed land with reduced submergence can be utilized for recreation, public/semipublic utilities, artificial recharge, conservative farming etc. for improving the riverfront and contiguous urban environment.

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