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Modeling flood inundation in floodplain of the Jamuna River using HEC-RAS and HEC-GeoRAS

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Abstract

Bangladesh lies at the confluence of world's three major rivers, namely the Ganges, the Jamuna and the Meghna. In Bangladesh, normally four types of flood expressly river flood, flash flood, tidal flood and storm surge flood appear. The Jamuna River is most vulnerable to river flood. As a low lying country, flood occurs repeatedly in Bangladesh and cause tremendous losses in terms of property and life, particularly in the low land areas. At least 20 % areas are flooded every year and in case of severe flood 68 % areas are inundated. Therefore, the study is carried out to develop flood extend map and flood inundation depth map of the Jamuna River. One dimensional hydraulic model HEC-RAS with HEC-GeoRAS interface in co-ordination with ArcView is applied for the analysis. The coefficient of determination (R^2) has been found as 0.98, 0.97, 0.82 and 0.81 for steady calibration, steady validation, unsteady calibration and unsteady validation respectively. The NSE values have been found greater than 0.60 for both calibration and validation. Among the five frequency analysis distributions, Log Normal distribution is best fitted with the observed discharge data at Bahadurabad station. The results of 2, 5, 10, 25, 50 and 100 year return period flood frequency analysis based on maximum flow are 65772, 76871, 83519, 91299, 96703 and 101790 m3/sec respectively. The percentages of area inundated by 2, 5, 10, 25, 50 and 100-year return periods floods are 26.12, 46.10, 51.14, 54.63, 56.89 and 59.19% respectively, corresponding to above discharge. The flood inundation area increases with the increase of return period. It followed into the log curve y=249.84ln(x)+1789.3. The classification of flood depth area showed most of the flooding area had water depth between 1.2 m to 3.6 m. The assessment of the flood inundated area showed that 41.99% and 30.83% area are of low land and very low land respectively for the 100-year return period flood. Thus, finding of the study may help in planning and management of flood plain area of the Jamuna River to mitigate future probable disaster through technical approach. Finding of the study may also help to determine suitability of building flood control structure like embankment, detention ponds for prevention purposes. The automated floodplain mapping and analysis using these tools provide more efficient, effective and standardized results and saves time and resources.

Keywords: Inundation, flood, Jamuna, HEC-RAS, HEC-GeoRAS.

1. Introduction

Bangladesh is located at the confluence of three major river basins: the Ganges, Brahmaputra and Meghna (GBM) basins. It's a low-lying country which land elevation ranging is from sixty meters to one meter above Mean Sea Level (MSL) (Islam 2012). Bangladesh is one of the most natural disaster prone nations in the world where storm surges, cyclones, floods, river bank erosions, and droughts are frequently occurred (Nasreen 2004). Among natural disasters in Bangladesh, flood is the dominant one. Bangladesh has experienced floods of a vast magnitude in 1974, 1984, 1987, 1988, 1998, 2000 and 2004 (FFWC 2005). The Floods of 1988, 1998 and 2004 inundated about 61%, 68 % and 38% of the total area of the country, respectively (Islam et al. 2007, Disaster Management Bureau 2010).

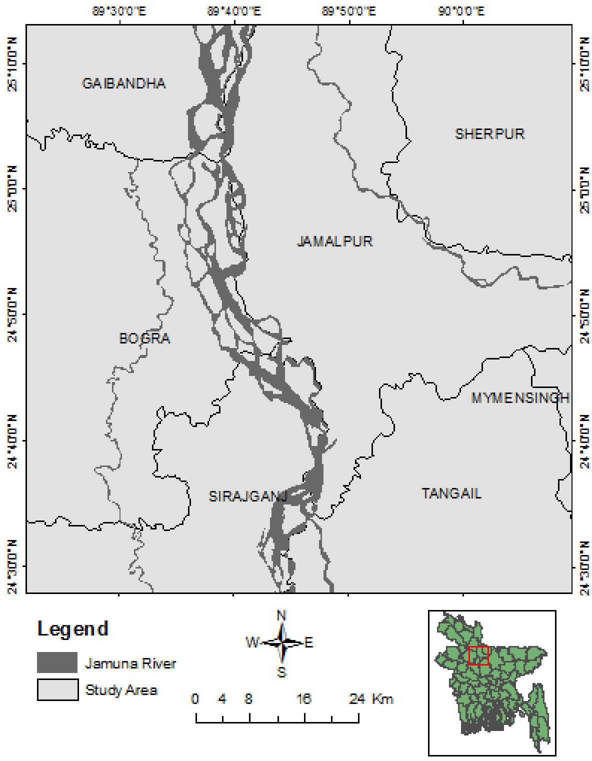

Fig. 1. Location of Jamuna river and its flood plain.

Extreme flood inundate large areas and cause widespread infrastructures damages, social disruptions in vulnerable groups and direct and indirect economic losses. The flood damage was USD 1.4, 2.0, 2.3, and 1.1 billion in the 1988, 1998, 2004 and 2007 severe flood's year in Bangladesh respectively (World Bank 2007). Bangladesh generally experiences four types of floods: flash floods, river floods, tidal floods and storm surges floods, nevertheless, vulnerability to these four types of floods varies according to different regions in the country. Mainly north-center parts of the country are affected by river flood. The Brahmaputra-Jamuna River, draining the northern and eastern slopes of the Himalayas, is 2900 km long where in Bangladesh the reach length is 240 km (Bhuiyan et al. 2010). The Jamuna, one of the dominant rivers of the country where river floods are a common phenomenon. Normally, 25-30% of the area is inundated during monsoon season along the river (Hossain 2003). In case of extreme flood events 50-70% of the country are inundated extending the areas far beyond the riverbanks (Hossain 2003) . The causes of Jamuna River floods are heavy rainfall in monsoon, snowmelt, enormous discharge coming from upstream, levee breaching, river siltation etc (Shardul et al. 2003, FFWC, 2008). The IPCC research reported that Bangladesh is highly vulnerable to climate changes (IPCC 2013). According to (IPCC 2013) both monsoon rainfall and sea level will be raised. Because of increased monsoon rainfall and raised sea level, flood inundation will be affected. The structural and non-structural measures are practiced to mitigate flood in Bangladesh. The Flood extend and inundation depth mapping, as a non-structural measures, are a vital component for appropriate land use planning in flood-prone areas. Though flood inundation modeling requires a two dimensional model, however, study of flood inundation can be done using a one dimensional (1D) hydrodynamic model which includes flood plains as a part of its domain. For example, HEC-RAS and HEC-GeoRAS were being used widely to develop flood inundation map in many studies (Hazarica 2007, Kneb et al. 2005, Hicks and Peacock 2005, Aabera 2011, Khan 2009). Most of the studies have been done in abroad. Flood extends and inundation depth mapping studies using mathematical model in Bangladesh are limited. In Bangladesh, a few studies have been done using satellite images and GIS (Bhuiyan 2014, Islam et al. 2010, Hasan 2006). The automated floodplain mapping and analysis using HEC-RAS and HEC-GeoRAS tools will provide more efficient, effective and standard results and saves time and resources. The outcome of this study will help the planner to prepare river flood warning maps to reduce the sufferings of people, damage of crops and vegetation, and destruction of infrastructures.

2. Study area

The Jamuna watershed lies in North-Central and North-West Zone of Bangladesh. The Jamuna's middle portion and its floodplain, about 25 km in the left bank and 35 km in the right bank of the river, are the study areas in this study (Figure 1). Its extends between 24°28'26" to 25°12'8" N latitude and 89°23'38" to 90°7'30" E longitude. The river reach length is about 100 km and the total area is 5858 square km. The study areas have been chosen based on the 1998 flood's inundation areas which are the maximum inundation areas of the Bangladesh. Only the Jamuna River's floodplains have been considered for this study which includes the following districts: Gaibandha, Bogra, Sirajganj, Sherpur, Jamalpur and Tangail.

3. Data collection and methodology

3.1 Data collection

Distinct sets of data were collected from different organizations for this study. Among the collected data, geometric data like bathymetry of the river, hydrologic data like discharge, water level, flood inundation map and digital elevation model as land topographic data were included. All collected data are summarized in the Table 1. The Jamuna River bathymetric data and DEM have been used for the model river bathymetric with flood plain setup. The discharge and water level data have been used for model boundary condition and calibration and validation. The 2004 historical flood map has been used for the comparison with model generated flood map.

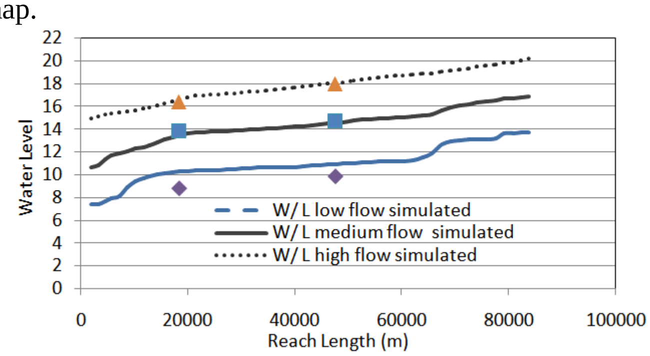

Fig. 2. Observed and simulated water level for steady simulation (Calibration)

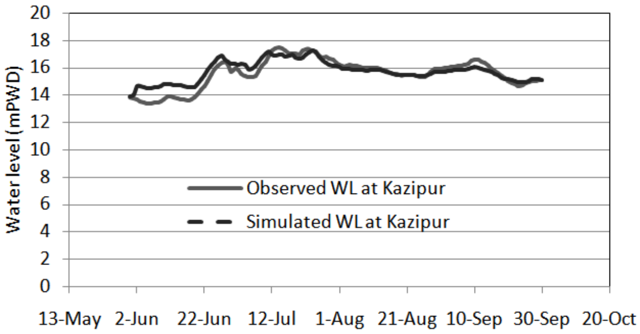

Fig. 3. Observed and simulation hydrograph at Kazipur (Calibration)

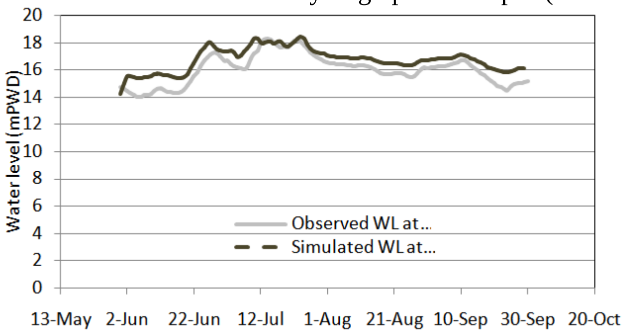

Fig. 4. Observed and simulation hydrograph at Mathurapara (Calibration)

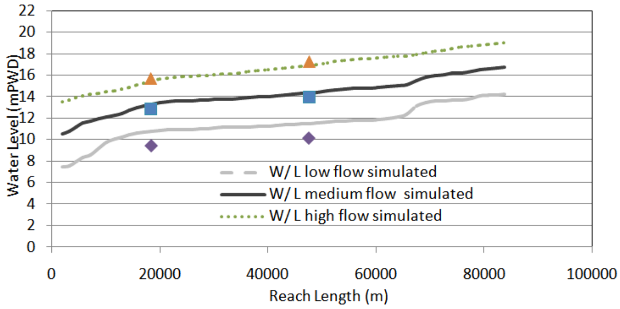

Fig. 5. Observed and simulated water level for steady simulation (validation)

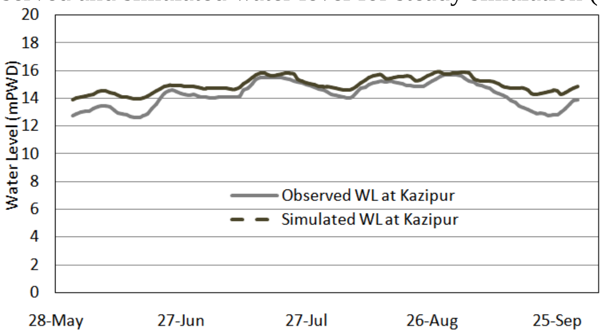

Fig. 6. Observed and simulation hydrograph at Kazipur (validation)

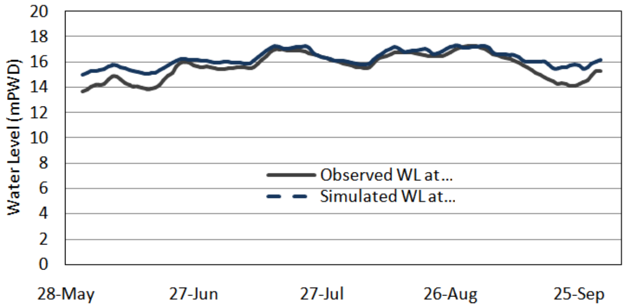

Fig. 7. Observed and simulation hydrograph at Mathurapara (validation)

Table 1
Collected data list

Data Type	Source	Data location	Periods
Bathymetric data	IWM	Jamuna River	2011
Discharge data	BWDB	Bahadurabad station	1956-2012
Water level	BWDB	Sirajganj station	2001-2007
Water level	BWDB	Kazipur station	2004-2005
Water level	BWDB	Mathurapara station	2004-2005
DEM	NASA	Bangladesh	2014
Flood map	FFWC	Bangladesh	2004

Table 2
Peak discharge for various return periods at Bahadurabad station

	Return Periods (years)					
Methods	2	5	10	25	50	100
Normal (cumec)	66912	77428	83021	89027	92905	96362
Log-Normal (cumec)	65772	76871	83519	91299	96703	101790
Pearson Type- III (cumec)	65541	76798	83619	91626	97186	102411
Log-Pearson Type- III (cumec)	66482	77613	84199	91831	97086	101999
Gumbel (cumec)	64758	75923	83315	92655	99584	106461

3.2 Frequency analysis

The flood frequency analysis is essential to interpret the past record of flood events in order to evaluate future possibilities of such occurrences. Frequency of a hydrologic event, such as the annual peak flow is the probability that a value will be equaled or exceeded in any year. The length of record should be sufficient to justify extrapolating the frequency relationship. For example, it might be reasonable to estimate a 50-year flood on the basis of a 30-year record, but to estimate a 100-year flood on the basis of a 10-year record would normally be absurd (BWDB 2010). Frequency analysis is cautioned when working with shorter records and estimating frequencies of hydrologic events greater than twice the record length (Viessmanand and Lewi 1996).

Table 3
Goodness of fit test among five distributions

Tests	Normal	Log-Normal	Pearson Type- III	Log-Pearson Type- III	Gumbel
PPCC	0.9759	0.9859	0.9858	0.9854	0.9855
Chi-Square	12.34	8.54	10.22	9.42	11.65

Table 4
Return periods and corresponding inundation area

Return Period (year)	Inundation area	% Inundation area
2	1263.85	26.12
5	2230.89	46.10
10	2474.44	51.14
25	2643.41	54.63
50	2752.97	56.89
100	2864.34	59.19

To determine the discharge of Bahadurabad in response to 2, 5, 10, 25, 50 and 100-year return periods flood frequency analysis has been conducted based on the discharge data for the year 1956 to 2012. To select the appropriate distribution a total of five distributions have been compared in this study.

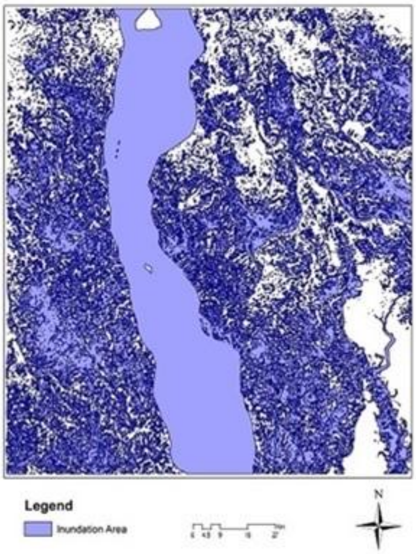

Fig. 8 (a). 2004 simulated flood map

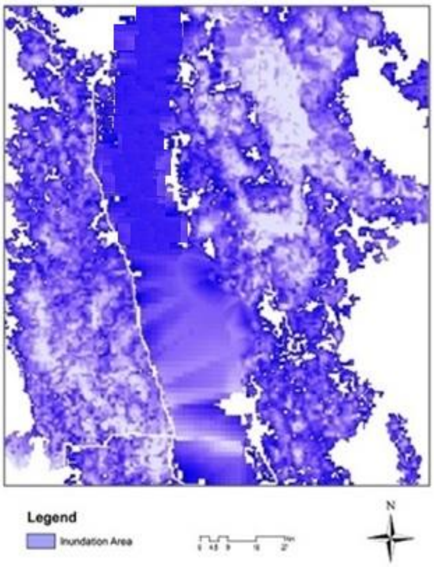

Fig. 8 (b). 2004 observed flood map

These are Normal Distribution, Log Normal Distribution, Pearson Type III Distribution, Log Pearson Type III Distribution and Gumble Distribution. There is an increasing trend of discharge at Bahadurabad gauge station of the Jamuna River. For selecting best fitted distribution, Probability Plot Correlation Coefficient (PPCC) and Chi-Square goodness-of-fit test has been conducted.

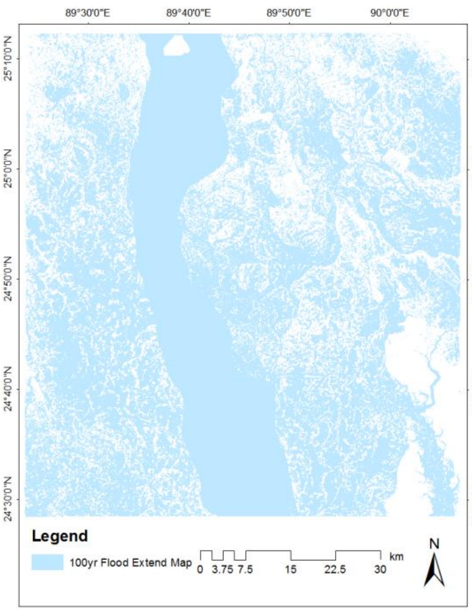

Fig. 9. Map of extent of flood for 100 year return period.

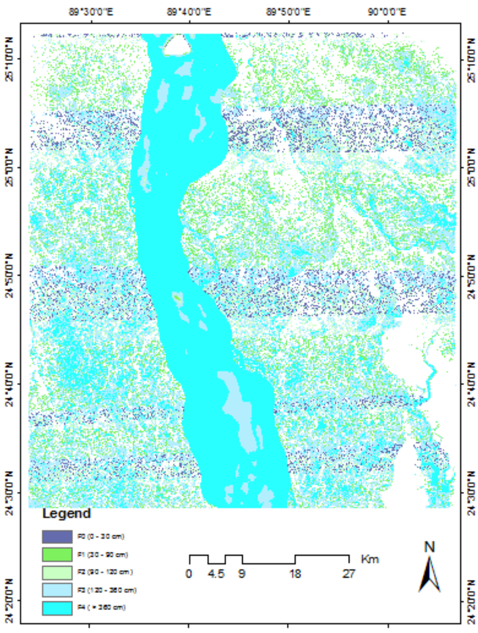

Fig. 10. Flood inundation depth map for 100 year return period.

3.3 Model development

The bathymetric grid has been created from bathymetric data by using Arc GIS. The bathymetric grid has been merged with topographic DEM to produce the complete bathymetry. The geometric data for HEC-RAS model has been extracted from the complete bathymetry by using HEC-GeoRAS. The HEC-RAS model will be calibrated and validated against the observed water level data. HEC-RAS has been used to simulate different known flood events. HEC-GeoRAS will be used to generate flood inundation maps. Historical flood event 2004 of Bangladesh has been compared with the resulting maps from the HEC-GeoRAS model. The future flood inundation maps of the Jamuna River will be developed for different return periods using HEC-GeoRAS.

4. Model calibration and validation

The one-dimensional model has one upstream discharge boundary and one downstream water level boundary. The data of 2004 and 2005 have been used for calibration and validation respectively, for both steady and unsteady flow simulations. Above data also have been used as a HEC-RAS model boundary condition.

4.1 Steady flow calibration

Water level calibration has been done at two stations namely Kazipur and Mathurapara. The hydrodynamic calibration mainly involves adjustment of bed resistant (Manning's ‘n’). Numbers of trial simulations were performed to verify the selection of the ‘n’ and finally ‘n’ value as 0.022 for main channel and ‘n’ value as 0.037 for flood plain has been fixed as Manning's ‘n’. Steady flow calibration is shown in Figure 3. Coefficient of determination (R^2) and Nash and Sutcliffe Efficiency (NSE) have been found 0.98 and 0.94 respectively for the steady flow calibration. Figure 3 shows maximum and medium flow simulations are better fitted to the observed data then the lower flow.

4.2 Unsteady flow calibration

The model has been simulated using the daily hydrograph for four months from June to September in 2004. For this study, effort has been made to calibrate Manning's roughness coefficient for single value using a foresaid data and subsequently, different values have been used to justify their adequacy for simulation of flow in the Jamuna River. Finally, ‘n’ value as 0.022 for main channel and ‘n’ value as 0.037 for flood plain has been fixed as Manning's ‘n’. The comparison of observed and simulated stage hydrograph at Kazipur and Mathurapara gauging station has been shown in Figure 3 and 4 respectively. Further, the flood peak and time to peak for the flood year 2004 is computed and it is observed that there is a close agreement between the observed and computed values. Coefficient of determination (R^2) and Nash and Sutcliffe Efficiency (NSE) have been found 0.82 and 0.65 respectively for the unsteady flow calibration.

4.3 Steady flow validation

The comparison of observed and simulated flow at Kazipur and Mathurapara gauging stations are shown in Figure 5. From the fig. it is shown that the observed data are in close agreement with the observed data. The value of coefficient of determination R^2 and Nash and Sutcliffe Efficiency (NSE) have been found 0.97 and 0.91 respectively.

4.4 Unsteady flow validation

The comparison of observed and simulated flow hydrograph at Kazipur and Mathurapara gauging stations are shown in 6 and 7 respectively. The Figure shows the simulated flood hydrograph is in close agreement with observed hydrograph. Coefficient of determination (R^2) and Nash and Sutcliffe Efficiency (NSE) have been found 0.81 and 0.63 respectively for the unsteady flow calibration.

4.5 Qualitative comparison between model and observed 2004 flood map

The calibrated and validated model has been used to generate water surface profiles for 2004 flood flow condition. Finally, this water surface has been used to generate 2004 flood map. Qualitative comparison between simulated and observed 2004 flood map is shown in Figure 8(a) and 8(b). Fig. shows that the inundation areas between simulated and observed are adequately alike.

5. Results and discussion

5.1 Results of flood frequency analysis

The results of 2, 5, 10, 25, 50 and 100 year return period flood frequency analysis based on maximum flow recorded at Bahadurabad (Station ID 46.9L) from year 1956 to 2012 excluding 1971 using Normal Distribution (N), Log Normal (LN), Pearson Type - III Distribution (P3), Log Pearson Type - III Distribution (LP3), and Gumbel Distribution (EV1) method are summarized below in Table 2. There is an increasing trend of discharge at Bahadurabad gauge station of the Jamuna River. For selecting best fitted distribution, goodness-of-fit test has been conducted. The values of Probability Plot Correlation Coefficient (PPCC) and Chi-Square test have been shown in Table 3.

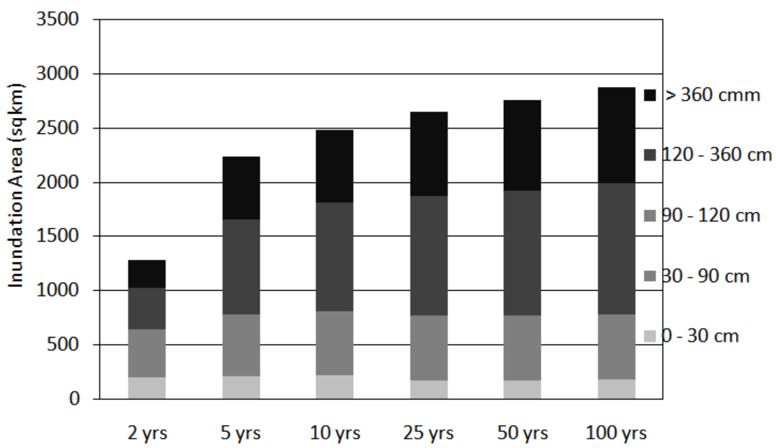

Fig. 11. Return period-flood depth relationship

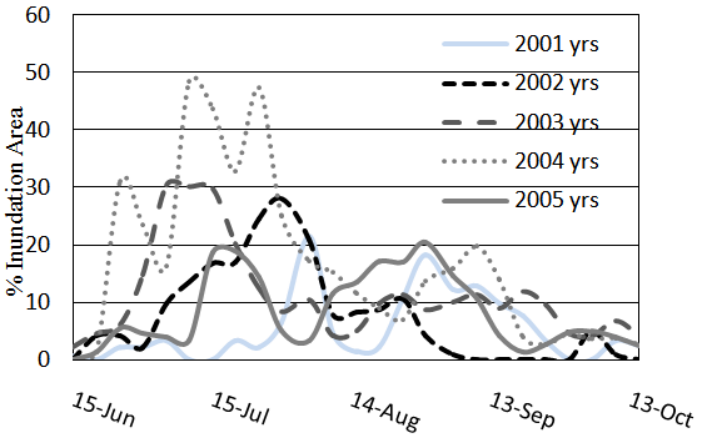

Fig. 12. Inundation area for different years at danger water level levee

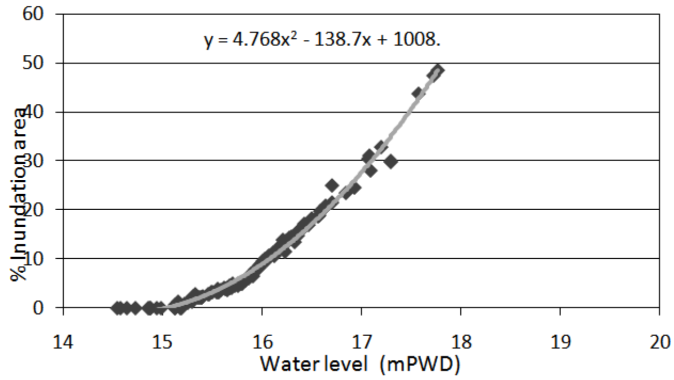

Fig. 13. Water level vs. % inundation area relationship at Kazipur station

The maximum PPCC value can be one that indicates that the method is completely fit. Again it is know that if Chi square is equal to zero the theoretical and observed frequencies agree exactly; while if chi square is greater than zero they do not agree exactly and the larger the value of Chi square the greater is discrepancy between the observed and expected frequencies. From Table 3 it is seen that chi square is minimum for Log Normal distribution and PPCC is higher for Log Normal distribution. Considering the two goodness of fit test the Log Normal is the best distribution among the five distributions for this station discharge data .The discharges from Log Normal (LN) distribution method have been used for future flood modeling.

5.2 Flood inundation extent analysis

Maps of flood extended of different return periods have been developed, among these maps only 100 year return period flood map is shown in Figure 9. Inundation area and the percentage of inundation area with return periods are shown in Table 4. Maximum and minimum inundation areas are 59.19% for 100-year return period and 26.12% for the 2-year return period respectively. For other return periods i.e. 5, 10, 25, and 50-year % of inundation area are 46.10, 51.14, 54.63, and 56.89% respectively.

5.3 Flood inundation depth analysis

Flood inundation depth maps of the study area for 2, 5, 10, 25, 50 and 100 year return period have been prepared, among these maps 100 year flood inundation depth map is shown in Figure 10. In the study, inundated areas are defined into five qualitative inundation depth classes viz. F0 (very high land (0m - 0.3m)), F1 (high land (0.3m - 0.9m)), F2 (medium land (0.9m - 1.2 m)), F3 (low land (1.2m - 3.6m)) and F4 (very low land (> 3.0m)) based on the inundation depth. The results of this assessment are summarized in Figure 11.

The classification of flood depth areas indicates that 33 to 42% of the total flooded areas have been inundated by water depth between 1.2 to 3.6 m and 28 to 31% of the total flooded areas have been inundated by water depth greater than 3 m. The total area under the water depth 0.3m is 6 to 15%.

5.4 Unsteady flow and flood inundation analysis

Flood inundation area simulated by unsteady flow simulation for different years is shown in the Figure 12, whereas levee water level has been considered as a river bank elevation. Figure 12 shows, about 49% area was inundated in 2004 and about 31% area was inundated in 2003. For the other years, different percentage of area was inundated. Normally floods arose in the month of July and sometime it appeared earlier in August.

5.5 Relation between water level and inundation area

The relation between water level and inundation area is shown in Figure 13. Water level at Kazipur gauge station corresponding to discharge is considered to determine the relationship between inundation areas with water level. Up to 15.12 m water level the area is not inundated. The inundation area increases with the increase of water level after 15.12 m river water level. The increasing inundation area with respect to water level is followed by two degree polynomial equation $y=4.77x^2-138.76x+1008.30$. This equation is developed from five years unsteady simulation water level and its corresponding inundation area. About 49% area is inundated for the 17.77 m water level at Kazipur.

6. Conclusion

The major tools used in this study are a one-dimensional numerical model HEC-RAS and ArcView GIS for spatial data processing and HEC-GeoRAS for interfacing between HEC-RAS and ArcView GIS. There is an increasing trend of discharge at Bahadurabad gauge station of the Jamuna River. Flood frequency analysis is considered to assess different return periods future maximum discharge for flood extend and inundation depth maps. Among the five distributions, the Log Normal Distribution (LN) is the best distribution for flood frequency analysis in this station. It is observed that flood frequency analysis by Log Normal (LN) discharges of 65772, 76871, 8519, 91299, 96703, and 101790 m^3/sec for 2, 5, 10, 25, 50, and 100 year return periods respectively. The flood inundation area increases with the increase of return period. It followed into the log curve y=249.84ln(x)+1789.3. For 2, 5, 10, 25, 50 and 100 year return periods 26.12%, 46.10%, 51.14%, 54.63%, 56.89% and 59.19% of the area were found to be inundated, respectively. In the 100-year return period 59.19 % land become inundated. The F0, F1, F2, F3 and F4 types land inundated area are 6.29, 13.31, 7.58, 41.99 and 30.83 % of 59.19 % respectively of total inundated land.

This method of floodplain mapping can be used as a useful tool for floodplain management and for decision making as well for future development within the flood plain of the Jamuna River basin.

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