

# Probability of flooding and vulnerability assessment in the Ajay River, Eastern India: implications for mitigation

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**Abstract** Estimation of flood intensity for a desired return period is of prime importance for flood management through flood plain zoning. Flood frequency analysis enables estimation of the probability of occurrence of a certain hydrological event of practical importance by fitting a probability distribution to one that is empirically obtained from recorded annual maximum discharge and/or stage data. This case study considers the use of four probability distributions, namely Gumbel's extreme value distribution (EV-I), extreme value distribution-III (EV-III), log-normal (LN) and Log-Pearson Type III (LPT-3) in flood modelling of monsoon-dominated Ajay River and illustrates the applicability of goodness of fit (GOF) and *D*-index tests procedures in identifying which distributional model is best for the specific data. Twenty-five years (1985–2009) of existing and estimated annual peak discharge ( $Q_{\max}$ ) data have been used for analyzing the trend of flood occurrence. After identifying the best fit model, the peak gauge height data ( $h_{\max}$ ) are then analysed combining with geographic information systems (GIS) for predicting flood affected area and preparing inundation map at a specific return period (*T*). Results of the study showed that the LPT-3 distribution is better suited for modelling flood data for Ajay at Nutanhat in West Bengal. The computed  $Q_{\max}$  for

LPT-3 distribution are slightly higher as compared to the results obtained by EV-I, EV-III and LN which are used for vulnerability assessment. The analysis also predicts that the affected area will be ranging from 235 to 290 km<sup>2</sup> in near future (at 25- to 200-year *T*). These findings provide clear picture for the pattern of hydrological fluxes and aftermath in the next decades in lower Ajay River Basin (ARB). Sustainable planning and developmental measures that consider the modelled pattern of hydrological fluxes of the study area were recommended for decision making.

**Keywords** Flood frequency · Probability analysis · Goodness of fit (GOF) test · Flood estimation · Flood management

## Introduction

World's worst hazards and disasters tend to occur in the countries between the Tropic of Cancer and the Tropic of Capricorn which are coincidentally the poorer countries of the world. Among all kind of natural hazards and or disasters, floods are probably the most frequent, devastating and widespread, causing serious loss of life and economic damage (Mohapatra and Singh 2003; Wang et al. 2011; Sharifi et al. 2012). It is a recurring event for South Asian tropical rivers which is the result of copious rains associated with active monsoon conditions (Ramaswamy 1987; Dhar and Nandargi 2003; Mirza 2011). Recently, the damages of flood are increasing at a spectacular rate (Baker 2006) and the twentieth century witnessed a series of most unprecedented floods globally on account of the global warming and impacts of economic development over the past 25 or 30 years (Knox 2000; Macklin and Rumsby 2007; Syvitski and Brakenridge 2013). The Centre for Research on the

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Epidemiology of Disasters (CRED) reported an occurrence of about 2156 floods in the last three decades of the twentieth century, resulting in 206,303 deaths, affected more than 2.6 billion lives and caused an economic loss of nearly US \$ 386 billion (Guha-Spaur et al. 2004). India has been no exception to this situation and considered worst-flood affected country after Bangladesh (Agarwal and Narain 1991; Sinha 2008). The data maintained by the Central Water Commission (CWC), New Delhi demonstrated that on an annual average, 7.21 million ha of land is inundated and nearly 32 million people are affected by floods in India (Kale 2014). In addition, the disastrous flash flood of Uttarakhand (10–18 June 2013) and Jammu and Kashmir (first week of September 2014) due to cloud burst is forced to think about the magnitude, extremity and time of occurrence of sudden floods in the heavy monsoon dominated region of India, like the state of West Bengal. The traditional agrarian economy, low-lying floodplain settlements and high population density have been jeopardized by the vulnerability of floods in West Bengal. Approximately 55.8 % of the region and 3.8 mha areas are susceptible to floods (Kale 2003; Nath et al. 2008). The 20 million poor rural people are affected and the damage to standing agricultural crops alone was worth 3000 crore rupees by September 2000 disastrous flood (Chapman and Rudra 2007; Kadam and Sen 2012). To combat, various paraphernalia are required including construction (downstream flood defences), forecasting (for warning and evacuation), and land-use management. So, the emphasis on understanding vulnerability of flood dynamics for mitigating problem with detrimental results has increased manifold during the recent years. There have been attempts to quantitatively analyze the annual peak river discharge ( $Q_{\max}$ ) and stage (gauge height;  $h_{\max}$ ) data in this regard.

The dynamic and random nature of flood is governed by the laws of chance and can be interpreted in terms of probability. The procedure involved in interpreting dynamic hydrologic events is known as frequency-magnitude analysis (FMA) and the analysis is inevitable (Kar and Goswami 1997) as it determines the nature and intensity of different geomorphic processes to a great extent (Wolman and Miller 1960). Different studies were undertaken on FMA for flood data arising from systematic, historical and palaeo-flood records all over the world (Baker et al. 1979; Stedinger and Cohn 1986; Frances et al. 1994; Vaill 2000; MacDonald 2013). Most of the studies based on popular theoretical probability distributions (or frequency distribution functions), namely generalised extreme value (GEV), extreme value (EV), Log-normal (LN), Log-Pearson Type III (LPT-3) distribution, etc. The GEV distribution is frequently used distribution in Great Britain (Chow et al. 2010), whereas the LN distribution in China (Singh and Strupczewski 2002) and the LPT-3 distribution has been recommended by federal

agencies in the USA (Benson 1968; Wallis and Wood 1985). The validity of the results in the application of these probability distributions is theoretically subject to the hypothesis that the hydrological data series are stationary (Mujumdar and Kumar 2012), independent and identically distributed (Stedinger and Vogel 1993; Khaliq et al. 2006). Two common approaches exist for practical extreme value analysis, i.e., the annual maximum series (AMS) method and the peak-over-threshold (PoT) (Naden 1992) or partial duration series (PDS) method. An overview of these methods can be found in Hosking and Wallis (1987) and Madsen et al. (1997).

In this study, the lower part of Ajay River Basin (ARB) in West Bengal is chosen as flooding is quite common due to heavy downpours in the monsoon season (Sanyal and Lu 2009). Historical records by the Irrigation and Waterways Department, Government of West Bengal and geoarchaeological investigations (Panja et al. 2002, Roy Choudhury 2002; Samanta 2008; Roychoudhury and Rajaguru 2010; Roy 2012) established the fact that the study area has been suffering from floods since time immemorial. Five major high-magnitude floods took place in the last 20 years (1990–2010). These are flash floods of short duration and there are some pockets in this basin that are subjected to frequent inundation (Perumal and Sahoo 2007). The situation in this basin is worsening because it has been estimated that out of 619 *mouzas* (A '*mouza*' refers to the smallest administrative cum revenue unit of the Indian union which comprising one to a few villages), 493 *mouzas* or 79.65 % of the total *mouzas* are flood affected in this part. Majumdar (1938), Bose (1965, 1970), Mohalanobish (1968), Niyogi (1987), Chatterjee (2008), Mukhopadhyay and Mitra (2000), Mukhopadhyay and Mukherjee (2005), Sanyal and Lu (2009), Bandyopadhyay and Jana (2010), Dhar (2010) and Kadam and Sen (2012) have worked significantly on the genesis, magnitude and effects of floods, modelling hydrological fluxes focusing mainly on the destructive nature of floods. In spite of these voluminous works, further empirical observation and statistical analyses of the available hydrological data are needed for proposing effective flood mitigation measures. The present study deals with the AMS approach of FMA and probes into the evaluation of existing four probability distributions using peak hydrological data. It also tries to find out the best model in fitting annual peak discharge data ( $Q_{\max}$ ). To verify the suitable distribution that best describes the annual maximum flood, the goodness of fit (GOF) tests (Zhang 2002) and *D*-index test have been performed. The best fitting distribution is used on peak gauge height for further estimating the flood affected area and inundation mapping within the lower ARB with the help of GIS. The results will be useful for decision-makers in view of spatial planning and future risk assessment.

## The Ajay River: geoenvironmental setting

The Ajay River is a medium-sized ( $\sim 6221 \text{ km}^2$ ) monsoonal river in eastern India which flows for a length of 299 km (Fig. 1a). It is one of the major western right bank tributary of River Bhagirathi (a distributary of the River Ganga) located in three states (Kadam and Sen 2012) viz. Bihar (Munger and Jamui districts), Jharkhand (Deoghar, Giridih and Dumka districts) and West Bengal (Bardhaman and Birbhum districts). The basin is funnel shaped with an area of  $\sim 2816 \text{ km}^2$  in its lower portion ( $23^\circ 25' \text{N}$ – $23^\circ 45' \text{N}$  latitude and  $87^\circ 15' \text{E}$ – $88^\circ 15' \text{E}$  longitude). An overall flow trend from northwest to southeast, the river originates from the Pre-Cambrian Archaean Gneissic complex of Chotonagpur massif and traversing for about 162 km (Chatterjee 2008); it encounters some outliers of Gondwana sedimentaries (Raniganj-Andal coal fields) of the Permo-Carboniferous age (Bhattacharya 2009). Subsequently, it flows over the Quaternary sequences divided into Older Pleistocene alluvium and Recent alluvium (Bhattacharya and Banerjee 1979) to meet the River Bhagirathi at Katwa ( $88^\circ 08' \text{E}$ ,  $23^\circ 39' \text{N}$ , at  $\sim 14 \text{ m msl}$ ), located 216 km upstream of Kolkata (Fig. 1a). On the plateau section, the Ajay receives three mighty tributaries, the Pathro and the Jayanti from the right and the Darua from the left above Sikatia of Deoghar district in Jharkhand. Below Sikatia, the basin is extended towards the east-southeast and ultimately culminates at Simjuri, near Chittaranjan ( $23^\circ 47' \text{E}$ ,  $86^\circ 55' \text{E}$ ) in West Bengal. After entering, it is guided by the faults of the Gondwana system in this area (Niyogi 1988) and joined by three tributaries, Hinglo (left bank) from north-west direction and Tumuni and Kunur (right bank) from south-west below Pandabeswar (Fig. 1b).

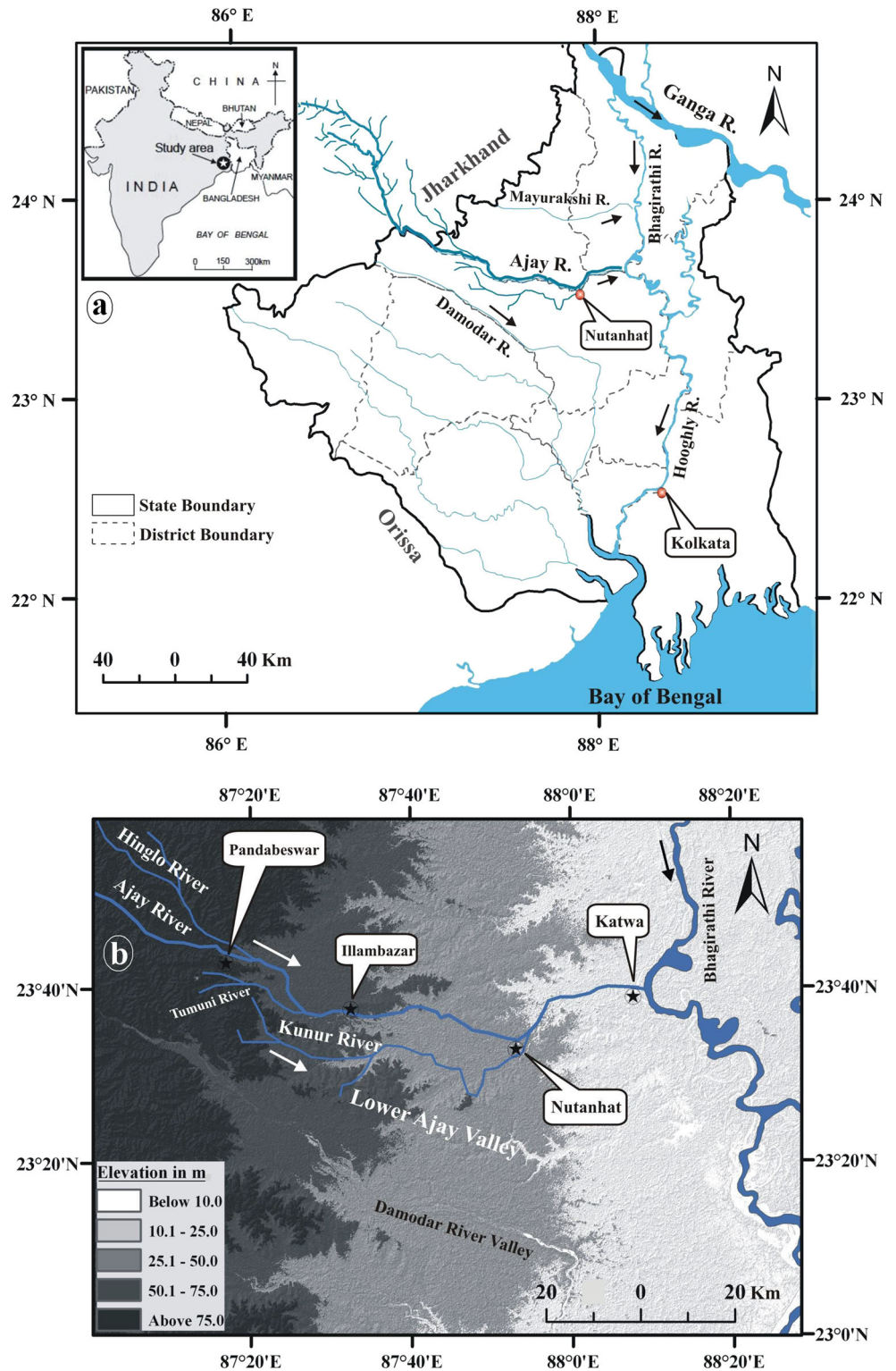
## Regional geology and geomorphology

The geology of the region (Fig. 2a) is dominated by Oldest Archaean (Pre-Cambrian) rocks (61 % of the total basin area) containing high-grade metamorphites, gneiss, schists and granites which are exposed in the western part of the study area (Niyogi 1998). In the Archaean formations, sedimentaries also occur and these were originally deposited as sandy, clayey and calcareous sediments (Banerjee and Bhattacharya 1973). The exposed part of the Archaean shield is characterized by a number of intracratonic Gondwana basins covering 8 % of the basin area around Asansol and Raniganj, forming parts of the Raniganj coalfield (Das 1969). Geological observations revealed that the Gondwana litho units comprising (1) Barakar Formation: quartzo felspathic sandstone with variety of shale and coal seams, (2) Barren Measures: hard crystalline clay ironstone with the absence of coal seams, (3) Raniganj

Formation: micaceous felspathic sandstone with calcareous clayey matrix, siltstone and shale often interlaminated with fine grained sandstone and coal seams, and (4) Panchet Formation: cross-bedded sandstone and bright red clay, conglomerate at base (Ghosh 2002). The Quaternary sediments, overlying unconformably the Tertiary deposits, are described as older alluvium or high level terraces, consist of indurated yellowish or reddish clays with gravels, sand, latosols and pedocal layer in some areas of lower basin. The recent sediments or newer alluvium were deposited as floodplain sediments of the Ajay and its several tributaries.

The study area ( $\sim 70 \text{ km}$  lower reach) stretches between the Mayurakshi basin on the north and the Damodar basin on the south (Fig. 1a). As far as its geomorphological setting is concerned, the Ajay River in association with its tributaries in lower ARB forms mosaics of meso- and micro-landforms. Topographic analysis based on Version 4 of Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (Fig. 1b) confirm the demarcation of lower reach from 80 m above msl and elevation ranges between 20 and 10 m consists mainly of flood plains. Field observations show four major geomorphic units in the study area, namely (1) slightly dissected gullied lateritic landscape (elevation  $\sim 50$ – $75 \text{ m}$ ) in the western part exhibits general slope 1:833 towards east and composed by hardcrust (3–5 m thick) and the mottle clay (5–8 m thick) containing ferruginous nodules (size  $\sim 3$ – $50 \text{ mm}$ ) (Bhattacharya and Banerjee 1979; Singh et al. 1998; Roy 2012); (2) terraced alluvial plain (elevation  $\sim 25$ – $50 \text{ m}$ ) lies east of the lateritic upland (Niyogi et al. 1968) comprising yellow, oxidized sand and clay with dirty white calcareous nodules (size  $\sim 0.5$ – $16 \text{ mm}$ ) and covering the highest grounds above the occasional and usual flood level; (3) older floodplain (elevation  $\sim 20$ – $40 \text{ m}$ ) of Ajay River which is occasionally prone to flood and embellished by depositional landforms, such as levee, back swamp, aggraded channel, crevasse, etc.; and (4) present day active floodplain characterized by channel-fill deposits and some scattered marshy lands lying at an elevation of less than 20 m. The river gradient above Pandabeswar is quite steep (1:713) that suddenly decreases (1:2273) up to Katwa causing flood inundation frequently below Illambazar (Niyogi 1987). Adopting Wentworth's technique, slope map was prepared from SRTM-DEM showing minimum slope ranging between  $0.4$  and  $0.6^\circ$  in the eastern, south-eastern and north-eastern part of the region (Fig. 2b). The minimum slope falls into the flat terrain area and the river in this area is a standing menace for flood hazards. There is an increase in slope angle westward in the range of  $0.6$ – $0.8^\circ$  and  $0.8$ – $1.5^\circ$ . Steep slope more than  $1.5^\circ$  is observed in isolated hilly areas. The variation of slope is largely attributed to topographic variation and an important factor for waterlogged situation in a flat terrain.

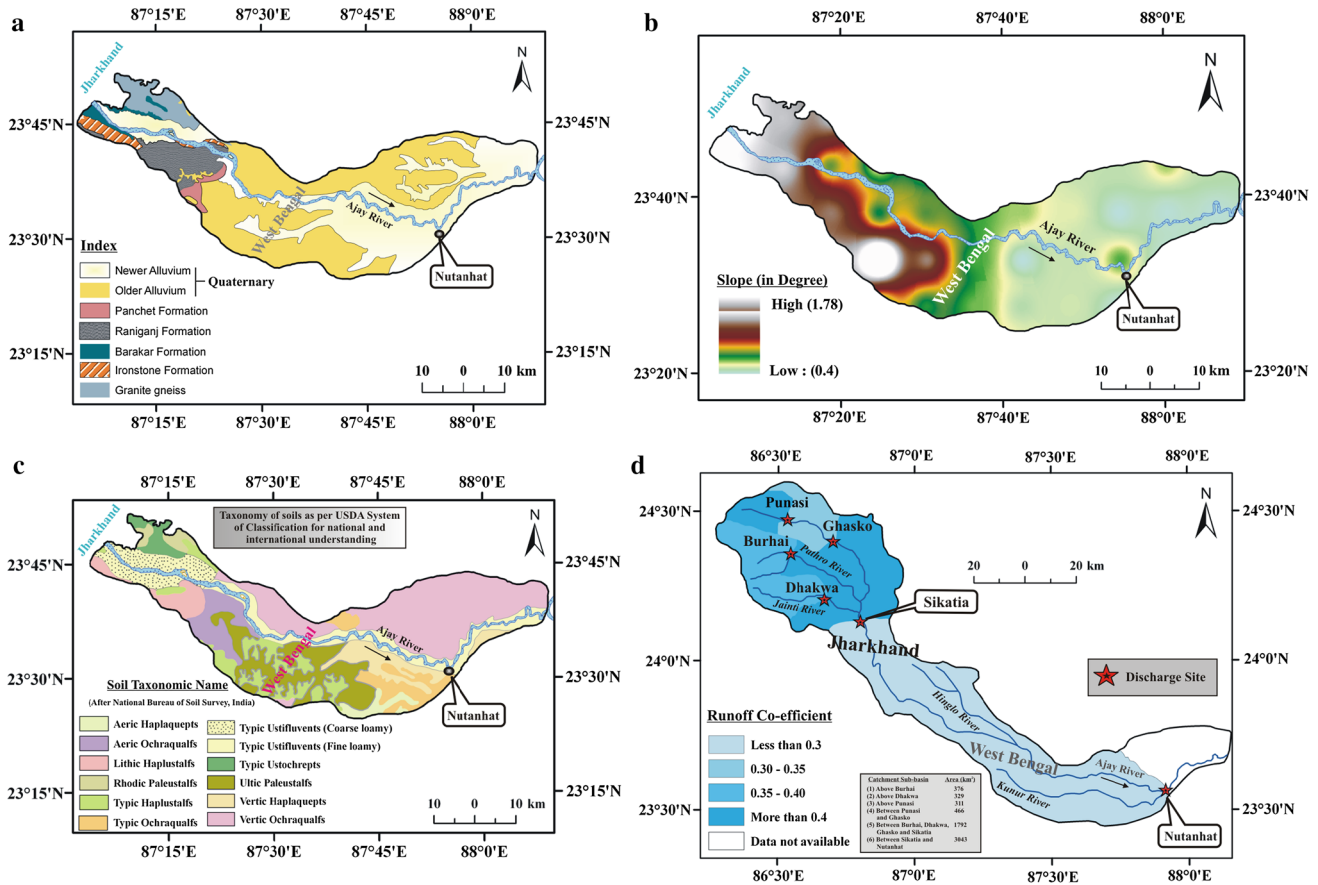
**Fig. 1 a** The Ajay River Basin (ARB) in south-western part of West Bengal. The location of the Nutanhat site is shown by *red filled circle*. The inset map shows the location of the lower part of ARB in India.  
**b** Physiography of the ARB based on SRTM-DEM (Version 4) with drainage network of the main river and places mentioned in the text



**Climate, soils and flood hydrology**

The catchment of the Ajay, including the Bihar and Jharkhand portion, forms an integral part of the monsoonal regime of Southeast Asia. The area is characterized by

distinct wet (June–October) and relatively dry (November–May) seasons, and the average annual rainfall varies from 1280 to 1380 mm (Niyogi 1991; NIH 1999–2000). Over 80 % of the annual rain arrives during the wet summer monsoon season (Niyogi 1985). The basin lies in the path



**Fig. 2** **a** Generalized Geological map of the Ajay river catchment in West Bengal (Source: geology compiled and simplified from GSI (1999) and Narula et al. 2000). **b** Slope map derived from Shuttle Radar Topography Mission data of 2000 showing the low values of average slope near Nutanhat gauging station. **c** Soil map showing different types of soils in the basin. The legend also provides taxonomy of soils as per USDA System of Classification for national and international understanding. *Aeric Haplaquepts* poorly drained fine soils, *Aeric Ochraqualfs* poorly drained fine loamy soils developed on old alluvium, *Lithic Haplustalfs* moderately well drained soils have a lithic contact within 50 cm of the soil surface, *Rhodic Paleustalfs* moderately well drained fine loamy soils, *Typic Haplustalfs* moderately well drained fine soils occurring on very gently sloping upland, *Typic Ochraqualfs* very deep poorly drained

fine soils, *Typic Ustifluvents (Coarse Loamy)* well drained coarse loamy soils occurring on level to nearly level meander plain, *Typic Ustifluvents (Fine Loamy)* well drained fine loamy soils occurring on very gently sloping flood plain, *Typic Ustochrepts* imperfectly drained fine loamy soils occurring on level to nearly level flood plain, *Ultic Paleustalfs* imperfectly drained fine loamy soils occurring on very gently sloping to undulating dissected upland, *Vertic Haplaquepts* poorly drained fine cracking soils occurring on nearly level to very gently sloping coastal plain with clayey surface, *Vertic Ochraqualfs* fine clay-enriched. (Source: National Bureau of Soil Survey, India 1992). **d** Intra-basin variation in the run-off in Ajay River Basin of eastern India including Bihar, Jharkhand and West Bengal. The inset table represents areal sharing of different sub-basins of the Ajay (Source: Niyogi 1988)

of tropical depression or cyclonic storms which forms in the Bay of Bengal in the monsoon period and moves generally in the north-west direction (NIH 1999–2000). So, the hydrological regime of the Ajay is influenced by the extreme fluctuations of the monsoonal rainfall (Niyogi 1988). Due to the occurrence of unusual heavy precipitation (33–38 cm in 2/3 days) in the catchment, the river level actually rises to a maximum height of 3.2–5.0 m during the months of peak discharge (August to September/October) which may last for only a very few days to overflow the banks and the sand-bars that occupy the higher relief areas of point bars (Bhattacharya 1972, 2009).

In rainy season, excess average annual rainfall with 75–80 % of the rainfall occurring in the monsoon months of June–September in the upper catchment area (Mukerji et al. 2009) raises the height of water level of River Bhagirathi and it refuses to receive and carry water from Ajay which in turn induces back flow and flood.

The spatial orientation of soil closely conforms to the basic structural layout of this region. After NBSS (1992), the soils encountered in the undulating dissected upland area of higher slopes are poorly to moderately drained yellowish brown to reddish brown, very shallow to moderate deep, light textural (skeletal) Lithic Haplustalfs, Ultic

Paleustalfs and Aeric Ochraqualfs type soils (Fig. 2c). In the lower convex and depression of very gently to gently sloping areas, the soils are of fine loamy and fine, pale brown to grey and dark grey, with red mottles, deep to very deep; and in the river terrace and levee of very gently to gently sloping areas developed over recent alluvium; the soils are fine to coarse loamy; basically Vertic Ochraqualfs and Typic Ustifluvents type. The slope and soil cover in the ARB including the hill catchment of Bihar and Jharkhand portion counteract each other on the run-off process significantly. There is marked intra-basin variation in the runoff co-efficient (Fig. 2d) indicating somewhat diversified geoenvironmental setting. In this basin, it varies from 0.29 to 0.45. The catchment area in between Ghasko, Burhai, Dhakwa and Sikatia in Jharkhand produces the highest runoff (0.45) due to steep slope and barren surface whereas below Sikatia in West Bengal the runoff co-efficient falls off considerably (0.29). Lesser slope in the flood plain areas reduces the amount of runoff directly and the presence of clay rich fine loamy soils with low infiltration rates in the lower part of the basin causing floods during monsoon.

The plains of ARB are characterized by one of the most intense flood affected region in eastern India (16 major floods in the last 100 years). In general, higher magnitude of slope in the western part of the ARB is favourable for quick run-off that accumulates in the lower part of the basin and drains out slowly through the trunk stream as the gradient becomes very gentle which contribute floods. The highest flood ever recorded on the Ajay River at Nutanhat in 1999 was of the order of  $2964.23 \text{ m}^3 \text{ s}^{-1}$ , which is comparable with some large floods of India. The peak discharge ( $Q_{\text{max}}$ ) for the 1999 event was  $\sim 2.6$  times higher than the average annual peak discharge ( $Q_{\text{m}}$ ) at Nutanhat (Fig. 3a). The ratios between  $Q_{\text{max}}$  and  $Q_{\text{m}}$  suggest that the peak discharges at both stations are variable and unpredictable. Annual data available for the Illambazar (Data source: from 1961 to 1965, Port Commissioners 1974; from 1999 to 2001, River Research Institute, Kolkata) and Nutanhat (Data source: mentioned in Table 1) gauging stations in West Bengal (see Fig. 1b for location) indicate that, within the last 100 years, high discharges in the range of  $1300\text{--}3000 \text{ m}^3 \text{ s}^{-1}$  were recorded on three occasions i.e. in 1961, 1999 and 2001. In terms of estimated flood size, the 1978 flood was the highest, although in terms of the quantum of devastation the 2000 flood event was the worst. The amount of flood affected area during 2000 flood was  $1488.85 \text{ km}^2$  in the study area (Mukhopadhyay 2009). Flood damage trend (Fig. 4c) represents a large area affected by 1956 ( $1425.45 \text{ km}^2$ ) and 1978 ( $1293 \text{ km}^2$ ) flood which crossed the mean flood affected area ( $999.87 \text{ km}^2$ ). After 1985, vulnerability also increases; however, 5-year moving average of flood shows a sharp

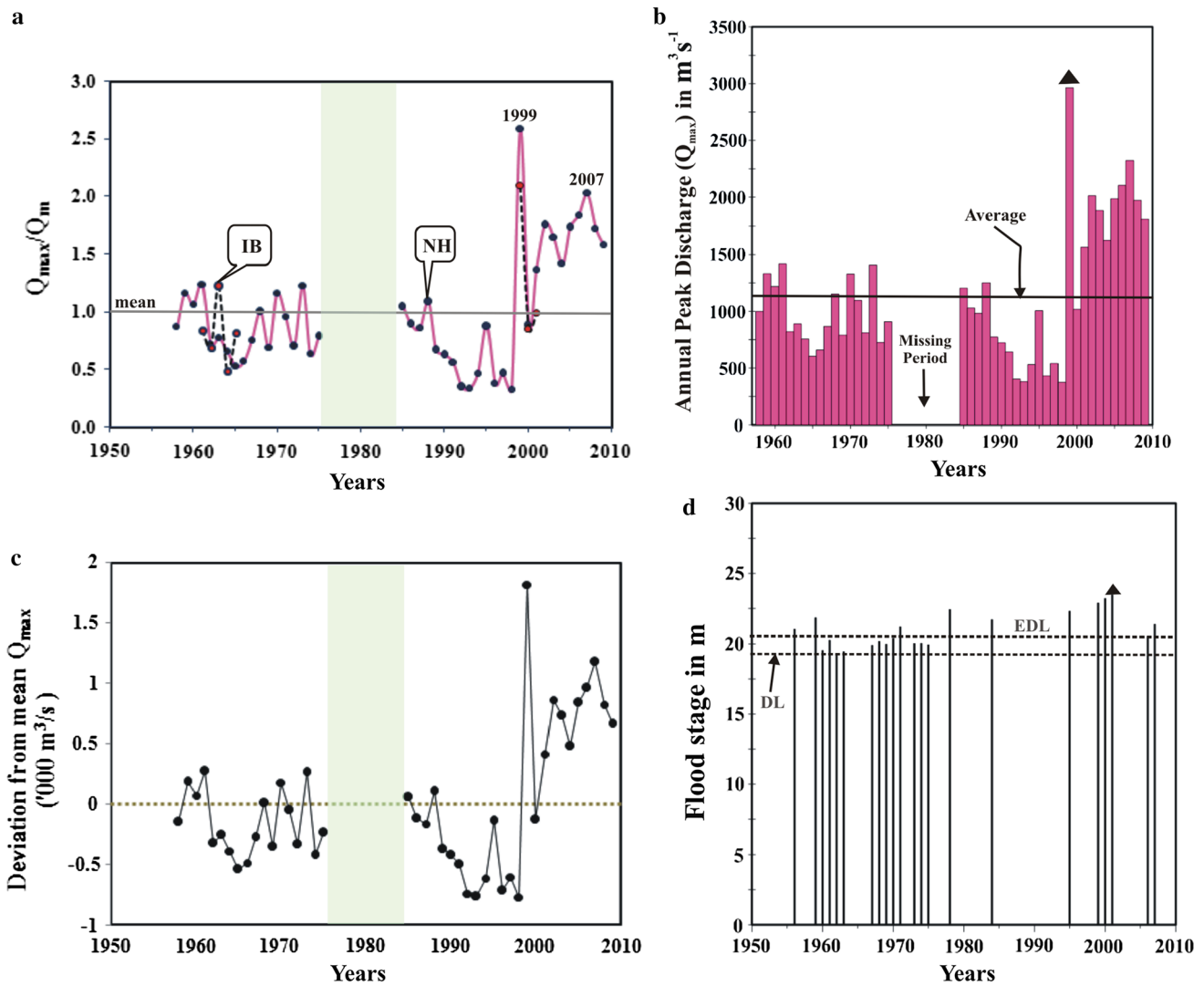
increase from 1995 to 2000. Before 1956, there are reports of large floods during September 1899, September 1922, August 1942 and September 1946 in lower Ajay River due to extensive heavy rainfall (Bose 1958; Das 1983; Mohalanobish 1968).

### Basin land use

The extent of man–nature interaction is manifested in the pattern of land use and human activities have profoundly changed the land. In particular, landuse and land management change affect the hydrology that determines flood hazard (Wheater and Evans 2009). Especially, the size of the effect of built-up development on stream flow will be greater where runoff is low, in catchments with permeable soils and geology. The basin of the Ajay is mainly under forest (a substantive amount in degraded state), cultivated land, waste land and built-up. These landuse classes are delineated from Landsat-1 MSS scene of 1973 and IRS-P6 LISS-4 scenes of 2014 and intense field verification (Fig. 5a, b). Around 68 % of the total area is under cultivation in 2014 which have got transformed from waste land in 1973. Several small urban settlements ( $\sim 16$  % of the total area in 2014) occur along the river, but most of the basin is rural. It seems that most of the land use/cover change has happened into the farming lands due to the increase in the population of the basin. The expansion of the built-up areas is one of the main reasons for reduction of permeable lands which further increases the surface floods and vulnerability. The comparison of the land use/cover types of the two images of 1973 and 2014, indicated that the area of the built-up have increased about  $113 \text{ km}^2$  in the 41 years (Fig. 5c).

### Nutanhat: description of study site

For the present study, the Nutanhat gauging site (Fig. 1) on the Ajay River was selected. The gauging site was preferred over other sites (Illambazar and Gheropara) because of several reasons—(1) uniform data as well as discharge and gauge height both data are available from this station, (2) the station has a record length exceeding 25 years, (3) more or less continuous and reliable discharge and gauge height data are available for more than 25 years, (4) the site represents the characteristics of a greater part of the lower basin area ( $\sim 75$  %), and (5) because of the location in lower reach, it represents the flood characteristics of the entire study area. At Nutanhat, the Ajay River has a well-defined, aggraded and high sinuous channel. The site is located about 45 km upstream of the confluence. The sand bed channel is about 15.8 m above sea level, and the longitudinal gradient is 0.0005. The top channel width is about



**Fig. 3** Hydrological characteristics of Ajay river system. **a** Time series plot of  $Q_{max}/Q_m$  ratio.  $Q_{max}$  = annual peak discharge and  $Q_m$  = long-term average peak discharge. *IB* Illambazar gauging station data, *NH* Nutanhat gauging station data. See text for source of data. **b** Graph showing the variations in the annual peak discharge ( $Q_{max}$ ) (recorded peak discharge from 1958 to 1975, 1992–2001 observed on a particular day during the whole year and rests are computed) record from 1958 to 2009 at the Ajay River; discharge station at Nutanhat (see Fig. 1). The highest peak discharge (shown by solid triangle) in this record was  $2964.234 \text{ m}^3 \text{ s}^{-1}$  on September 25, 1999. The thick line represents the value of  $Q_m$  ( $1146.769 \text{ m}^3 \text{ s}^{-1}$ ). **c** Plot of deviation of annual peak discharge

from mean for 43 years (1958–2009). **d** Record of the high flood stages on the Ajay River at Nutanhat. The lower dotted line represents the danger level (DL), which is approximately equal to the bankfull stage (19.19 m) and is the maximum safe level for the lower ARB. The upper dotted line (20.19 m) represents the extreme danger level (EDL) which is vulnerable for ARB (Niyogi 1987). The flood stage has been plotted as continuous annual peak discharge data are not available for the entire gauging period. The largest flood in terms of gauge height is shown by solid triangle. The shaded area in **a** and **c** represents the period (1976–1984) of missing data or data unavailability

130 m and during large monsoon flows, the maximum flow depth ranges between 6 and 7 m. The width-depth ratio during high-magnitude events is generally less than 35. Overbank flows are common and the river has less channel capacity to accommodate large flows. The channel in this reach is bordered by riverine aggradational plain formed of river borne older and recent alluvium. Floodplain overbank type deposits are observed within the unconfined flat alluvial banks which are dominantly composed of sandy-

silts. The channel floor is consists by sandy channel-fill deposits with mid-channel bars and laterally developed point-bars.

The time series plot (Fig. 3b) of maximum or peak annual flows ( $Q_{max}$ ) at Nutanhat site shows extreme ephemerality and variability. The river is also characterised by large inter-annual variability in discharges at this site. Figure 3c depicts that while the variability in the peak discharge was relatively lower from 1958 to 1975 and

**Table 1** Data used in this study

| Discharge or stage site | Latitude and longitude  | Data type/variable                            | Time-span | Missing period          | Data source  |
|-------------------------|-------------------------|---|-----------|-------------------------|--|
| Nutanhat                | 23°24'27",<br>87°54'56" | Annual maximum flood discharge ( $Q_{\max}$ ) | 1958–2009 | 1976–1991,<br>2002–2009 | 1958–1975: Port Commissioners (1974)<br>1992–2001: River Research Institute, Kolkata   |
| Nutanhat                | 23°24'27",<br>87°54'56" | Peak flood stage ( $h_{\max}$ )               | 1959–2009 | 1976–1984               | 1959–1975: Port Commissioners (1974)<br>1984–2009: Mukhopadhyay (2010), Irrigation and Waterways Directorate, Govt. of West Bengal |

1985–1988, the variability has increased significantly 1999 onwards. Interestingly, the 2001 flood (Fig. 3d) was the highest on record and more vulnerable to embankment breaching in terms of stage with a gauge height ( $h_{\max}$ ) of 23.48 m which crossed the danger level (DL; 19.19 m) and extreme danger level (EDL; 20.19 m). Average monthly discharge (1958–1965) indicate that discharge starts to peak in June and reaches a maximum in August, whereas during other months the river is characterised by greatly reduced discharge (Fig. 4a). Flows, important for the investigation from the standpoint of flood inundation, occur between June and October with mean daily discharges vary from 47.17 to 248 m<sup>3</sup> s<sup>-1</sup> (Niyogi 1991). In contrast, the average flow is reduced to only 13 m<sup>3</sup> s<sup>-1</sup> in the month of November and it becomes almost dry in the months of April and May (Niyogi 1987). In these months, at Nutanhat, surface flow almost disappears and the river channel contains a series of unconnected pools of stagnant water. The significant difference in river discharge between the non-monsoon and monsoon period is one of the major factors responsible for overbank flooding in this area. The monthwise stage data for different peak flow years at Nutanhat (Fig. 4b) indicates that most of the years experienced peak stage records during the months of September and October.

## Data and method of analysis

### Data set

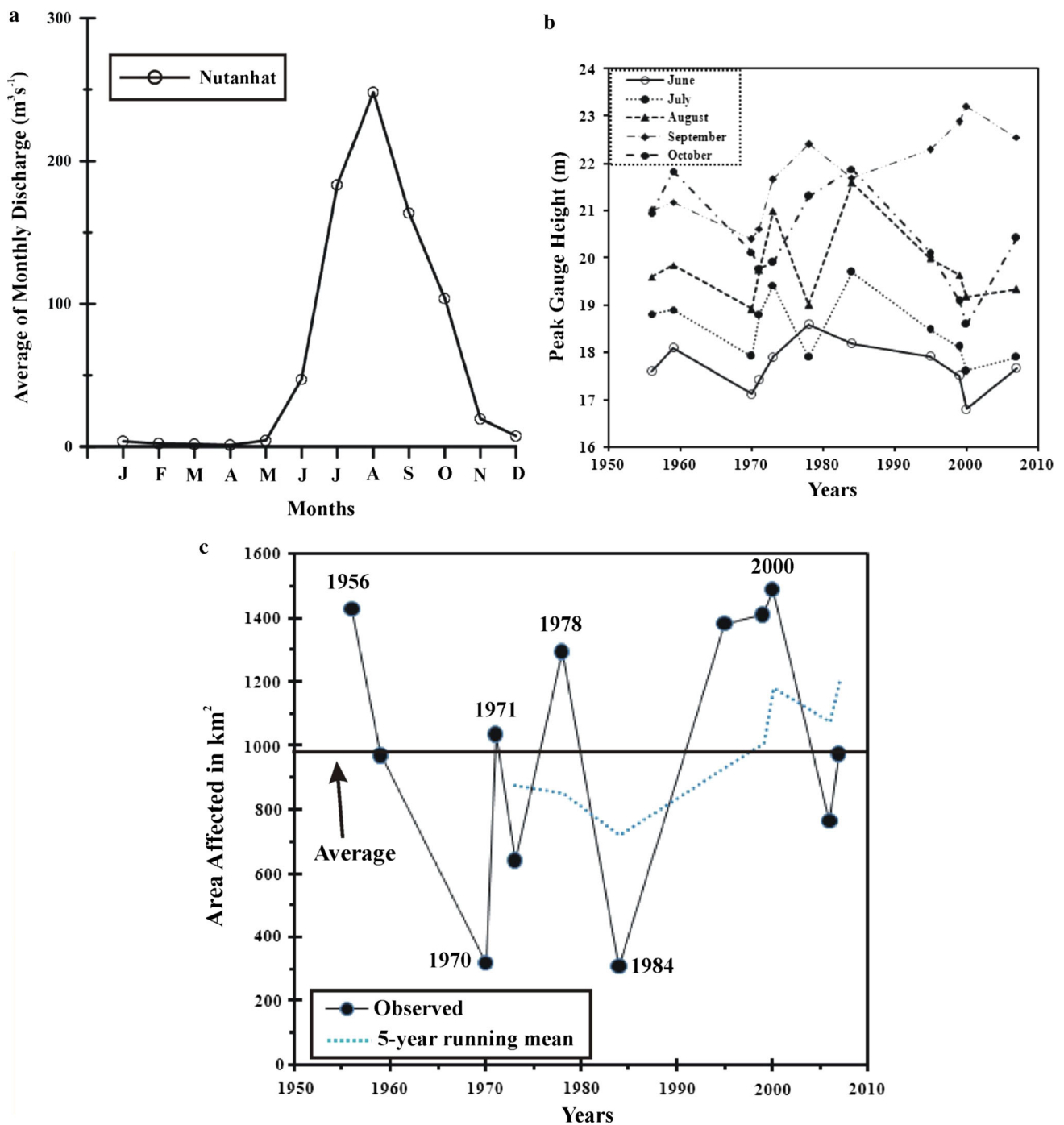
The data analyzed in this paper consist of long-term annual peak discharge/stage series available for Ajay River. The annual peak discharge/stage data is used as a flood response marker for a river (Burn and Arnell 1993). The data were mainly acquired from the River Research Institute (RRI), Kolkata; Irrigation and Waterways Department, Government of West Bengal, various published and unpublished reports. Continuous flood magnitude or stage data are not available for Ajay River at Nutanhat. The details of time span, missing period and sources of data are

given in Table 1. In the absence of continuous records, statistically significant power-law equation ( $h_{\max} = 15.99 Q_{\max}^{0.031}$ ) computed from peak discharge ( $Q_{\max}$ ) and gauge height ( $h_{\max}$ ) available for the period 1959–1975 were used to estimate the flood discharge for the missing period (1985–1991, 2002–2009). Although the relationship has a significant scatter (Fig. 6a), the method represents the only reasonable means of determining the missing flood magnitude. The present study deals with FMA using 25 years records of actual and computed discharge data over the period of 1985–2009. In addition, the continuous peak gauge height ( $h_{\max}$ ) data available from 1959 to 1975 are analysed using frequency analysis to estimate the flood affected area at different return period ( $T$ ).

### Flood probability analysis

In flood frequency analysis, the data collation involved a number of steps like selection whether annual maximum series (AMS) or peak-over-threshold (PoT) will be used in the modelling. Most of the literatures are dealing with the use of annual maximum series (AMS) in comparison to PoT. Because, in PoT approach, it is necessary to ensure that the chosen flood events are independent, that is, the assumption with PoT is that the abstracted peaks are mutually independent (Rosbjerg 1985). The flood peaks might not form an independent time series since some flood peaks may occur on the recession curves of the preceding flood peaks. IEA (1987) identified three advantages of using the AMS: there is a high probability that flood events are independent; the series is easily and unambiguously extracted; and the form of the frequency distribution of annual floods generally conforms to theoretical distributions. The other drawback of PoT is the data requires the selection of a minimum threshold value, which defines the events included in the PoT (Madsen et al. 1997). The choice of a threshold really becomes a balancing act. If the threshold is set low, many events are identified for the analysis, and some of these may be very small therefore being irrelevant especially for the higher quantile estimation. So, the AMS approach is used for modelling





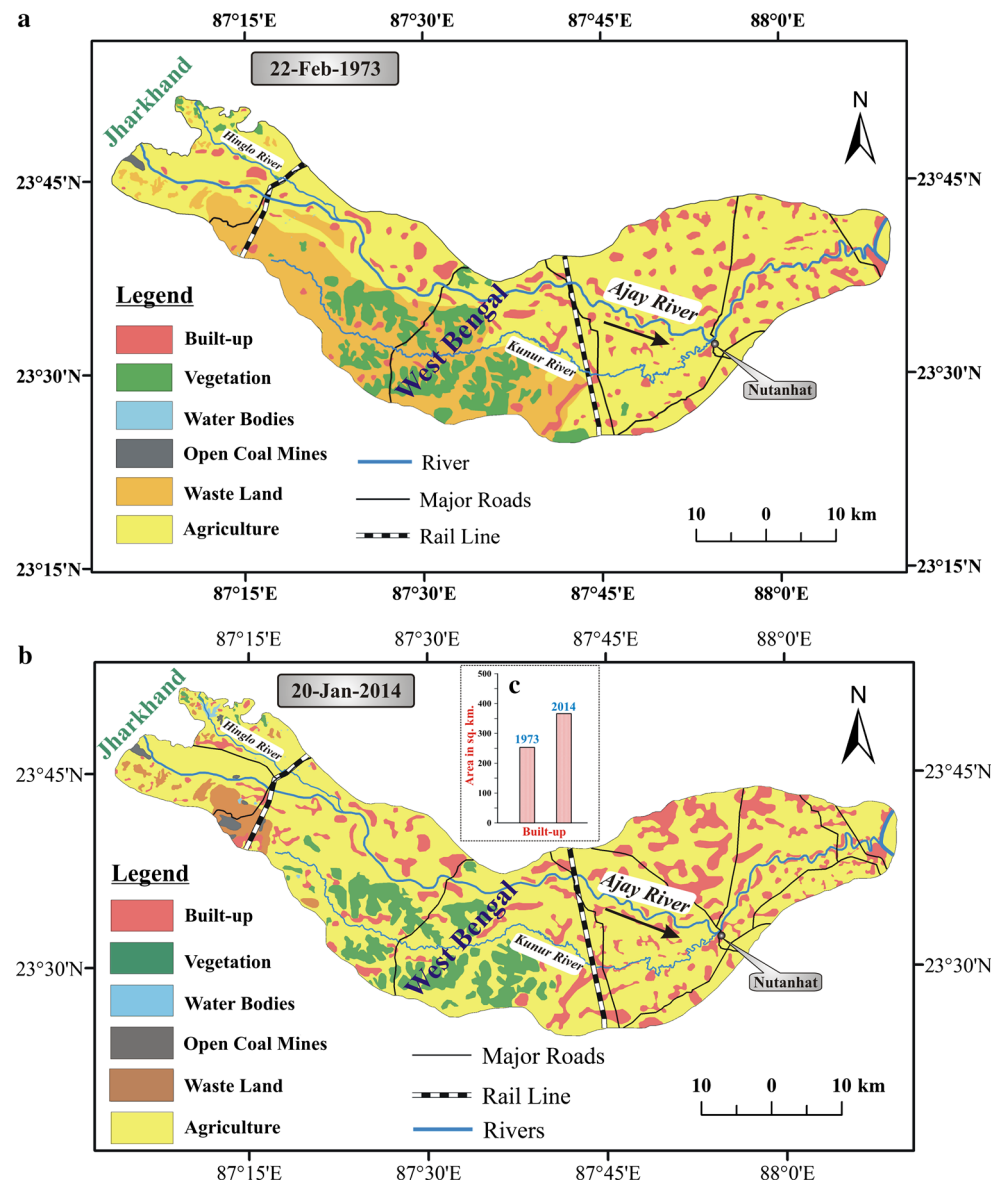
**Fig. 4** a Variation in average monthly discharge averaged for the period of 1958–1965; the peak occurs in the month of August. b Month-wise peak gauge height (m) in different flood years (1956–2007) of monsoon season (June–October) at Nutanhat gauging station (Source of basic data: Mukhopadhyay 2010; Irrigation and Waterways Directorate, Govt. of West Bengal). c Trend of flood

affected area in the lower ARB. The blue line represents the 5-year moving average of the area affected due to flooding. The thick line shows the average flood affected area (999.874 km<sup>2</sup>). The high and low flood affected years are labeled (Source of basic data: Niyogi 1987; Mukhopadhyay 2009)

hydrological data of Ajay River in the present study. The analytical method of flood frequency analysis usually involves fitting a probability distribution function to model the observed peak flow data from which the probability of

exceedance of flow-discharge of a particular magnitude flood may then be calculated. The methodology being followed here consists of techniques of FMA using four probability distribution functions by selecting annual peak

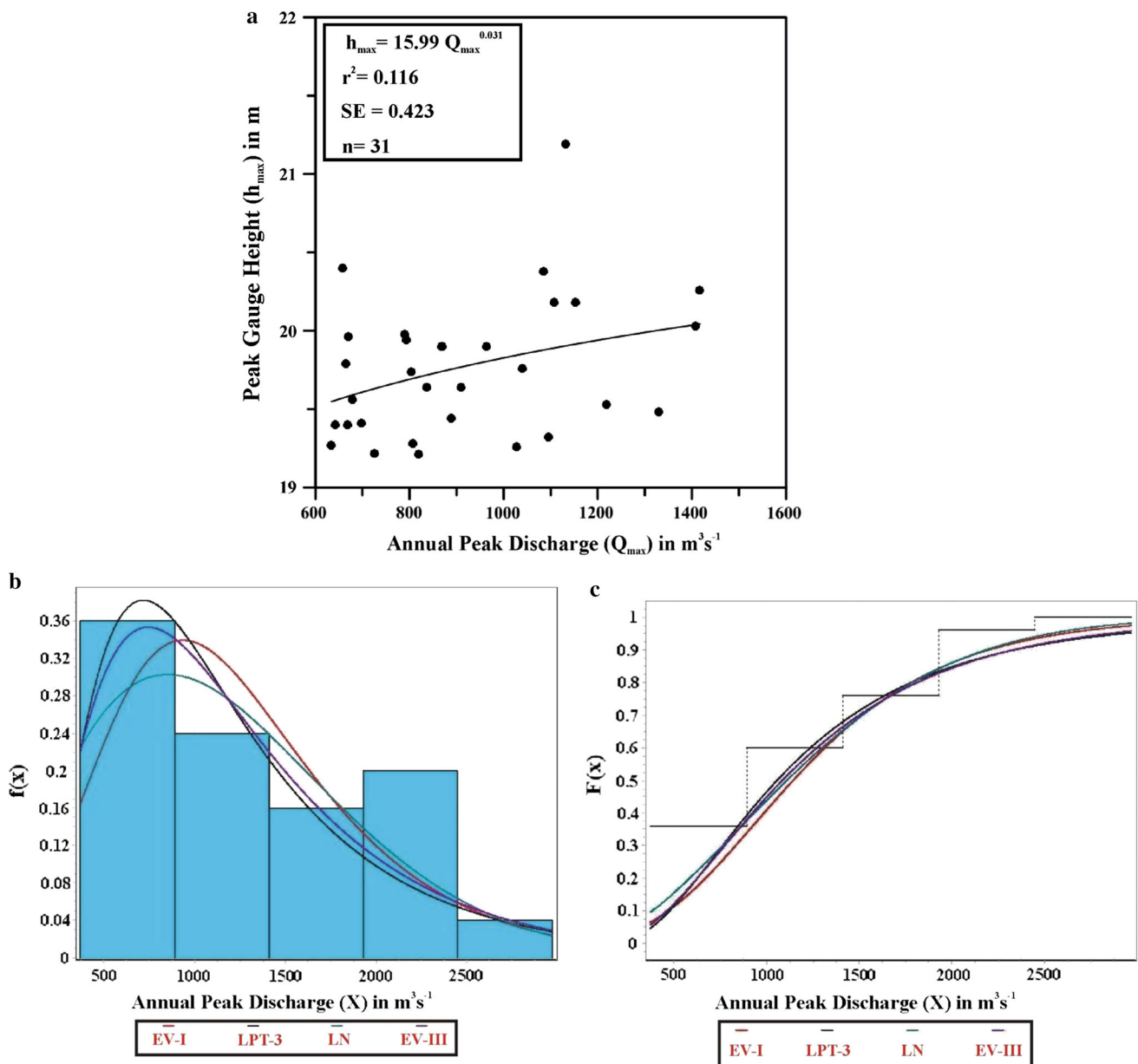
**Fig. 5** Ajay Basin in West Bengal: land use and land cover map of **a** 1973 and **b** 2014 (Source: maximum likelihood classification and subsequent digitization of the different land use and land cover area from Landsat-1 MSS scene of 1973 and IRS-P6 LISS-4 scene of 2014). **c** Distribution of the built-up area during the two periods (1973 and 2014) is shown in *inset diagram*. It indicates the significant increase in the built-up area within floodplain during 41 years



discharge ( $Q_{\max}$ ) and stage data ( $h_{\max}$ ) of Nutanhat. It involved to compute statistical parameters such as mean values ( $\bar{X}$ ), standard deviation ( $\sigma$ ) and Coefficient of skewness ( $\beta_1$ ) as well as estimated flood magnitude ( $X_T$ ) with probability of occurrence ( $P$ ) in  $T$ -year return period. In general, different probability distributions are fitted to estimate the exceedence probability of high magnitude floods (Kale et al. 1993). The two form of EV distribution (Chow et al. 2010); viz. EV-I (Gumbel's extreme value distribution) and EV-III (Weibull's method), LN and LPT-3 distributions were attempted in the present study to evaluate the efficacy of different techniques of flood analysis towards assessing the disastrous nature of floods. Models of annual maximum flood amount ( $X$ ) considering random variable are described with their probability

density functions  $f(X)$  and cumulative distribution functions  $F(X)$  after Chow (1964) is shown by Fig. 6b, c. For the estimation of parameters (Table 2) of the following probability models, the maximum likelihood estimation (MLE) method is considered because it provides population parameters with the least average error (Chow et al. 2010). EasyFit software (version 5.5) was used to get probability density functions  $f(X)$  and cumulative distribution functions  $F(X)$  as well as parameters which is available at <http://www.mathwave.com>. The data computation processes of probability models are studied employing following fundamental methods:

The EV-I distribution (Gumbel's extreme value distribution) is a double exponential distribution ( $F(x) = e^{-e^{-Y}}$ ) introduced by Gumbel (1941) and according to this theory,



**Fig. 6 a** Power-law relationship between annual maximum discharge ( $Q_{max}$ ) and peak gauge height ( $h_{max}$ ).  $SE$  standard error. The correlation coefficient ( $r = 0.34$ ) between the two indices is statistically significant at 0.05 level. **b** Probability density functions for

$Q_{max}$  of Ajay River using EV-I, EV-III, LN and LPT-3 distributions. **c** Cumulative distribution functions plots of recorded  $Q_{max}$  of Ajay River using EV-I, EV-III, LN and LPT-3 distributions

**Table 2** Estimated statistical parameters for the four distributions

| Sl. no. | Distributions                | Parameters |          |          |         |          |
|---------|------------------------------|------------|----------|----------|---------|----------|
|         |                              | $\bar{X}$  | $\sigma$ | $\alpha$ | $\beta$ | $\gamma$ |
| 1.      | Gumbel (EV-I)                | 937.18     | 561.69   | –        | –       | –        |
| 2.      | Weibull (EV-III)             | –          | –        | 1.7704   | 1365.0  | –        |
| 3.      | Log-normal (LN)              | 6.9627     | 0.62073  | –        | –       | –        |
| 4.      | Log-Pearson Type III (LPT-3) | –          | –        | 60.717   | 0.0813  | 11.899   |

the probability of occurrence ( $P$ ) of a flood ( $X$ ) to or larger than a value  $X_o$  is given by (Subramanya 1994):

$$P(X \geq X_o) = 1 - e^{-e^{-Y}}, \quad (1)$$

in which  $Y$  is a dimensionless variate. The dimensionless variate ( $Y$ ) can be described by equation: ( $Y = 1/0.78\delta(X_T - \bar{X}) + 0.577$ ) where  $X_T$  = the estimated flood in  $T$ -year return period. For computing the return period ( $T$ ) and computed discharge ( $X_T$ ), the following Eqs. (2), (3) are usually referred:

$$T = 1/(1 - e^{-e^{-Y}}) \quad (2)$$

$$X_T = \bar{X} + \delta K \quad (3)$$

in which  $K$  is the frequency factor ( $0.78Y - 0.45$ ). The technique of EV-III distribution, developed by Weibull (1939) is said that the probability ( $P$ ) of a flood of given  $m$ th rank, occurring in the  $n$  next year's simplified to relative frequency as  $P = m/(N + 1)$  and recurrence interval ( $T = 1/P$ ). In LN distribution, the data is normally distributed with the mean ( $\bar{X}$ ) and standard deviation ( $\sigma$ ) and the skewness coefficient ( $\beta_1$ ) is assumed to be zero. The  $X_T$  is given by:

$$X_T = \bar{X} + K\sigma, \quad (4)$$

where  $K$ , the frequency factor corresponding to a particular return period ( $T$ ) with  $\beta_1 = 0$  as per determined by the table in Haan (1977). In case of LPT-3 distribution which is a standard technique developed by Pearson (1930), the estimated discharge ( $X_T$ ) of a given period can be evaluated by the logarithm of the designed flood using equation:

$$\log X_T = \log \bar{X} + K\delta_{\log x} \quad (5)$$

where  $\log \bar{X}$  is the average of the  $\log X$ ,  $K$  is the frequency factor and  $\delta_{\log x}$  is the standard deviation of the  $\log X$  values. The frequency factor  $K$  in Eq. (5) is the function of  $\beta_1$  and  $T$  in LPT-3 and can be found using the frequency factor table (Haan 1977).

### Goodness of fit (GOF) and $D$ -index test

To use a particular distribution for reliable prediction of a flood event, it is necessary to find out the most appropriate method of flood frequency analysis for a river. Three different mostly used goodness of fit (GOF) tests, viz. Kolmogorov–Smirnov (K–S), Anderson–Darling (A–D) and Chi square ( $\chi^2$ ) tests either based on probability density functions  $f(X)$  or cumulative distribution functions  $F(X)$  were carried out to identify the best fit model. These tests calculate test-statistics, which are used to analyze how well the data fit the given distribution. All test statistics are defined in Solaiman (2011). The reason for selecting three different tests is that there is no single test that can give

conclusive results and a particular test emphasizes on a particular aspect of the GOF (Cunnane 1978). The tests are carried out at 5 % significance level. The GOF tests were executed in the EasyFit software (version 5.5). The results of all these tests have been shown in Table 3. The chosen distribution that best fits the annual maximum flood amount is based on the minimum error indicate by all these tests. In addition, the  $D$ -index test has been performed to confirm the best method for estimating flood magnitude and stage (Bhattacharya and Goswami 2002).  $D$ -index is given by:  $D = 1/\bar{X} (X_i \text{ observed} - X_T)$ , where  $\bar{X}$  is the mean of the observed data (Hazarika 2010). The distribution with lowest value of  $D$ -index will be considered as the best distribution for estimating peak discharge for a given return period. Thus, the best probability distribution method is used for mapping the flooded area and assessing the vulnerability of lower ARB.

### Affected area at different return period and inundation mapping

The flood affected area has been assessed and estimated from freely available SRTM-DEM (Version 4) of 3 arc second (ca. 90 m resolution) with geographic projection, which was procured from the CGIAR-Consortium for Spatial Information site (<http://srtm.csi.cgiar.org>). This processed SRTM data with a reported vertical accuracy of 7.58 m for Phuket Island of Thailand and 4.7 m in the Catskills Mountains in the USA (Gorokhovich and Voustianiouk 2006) is the most reliable dataset and has been supplemented with auxiliary DEMs to fill the data voids (Sanyal et al. 2013). The computation for extracting flood affected area is carried out employing the following methodology: (1) based on DEM; the basin area is demarcated using ArcGIS (version 9.3) software; (2) within drainage basin below Nutanhat, a point map is created on the basis of location of Nutanhat; (3) gauge heights of different return period at Nutanhat are calculated by LPT-3 method (suitable method after GOF and  $D$ -index test); and (4) all pixels at an elevation of lower or equal to the specified level (gauge heights) are multiplied with the spatial resolution of the DEM. The above mentioned process is applied for 25- and 100-year return period of floods. The 25-year inundation area map is generated and crossed with present day lower Ajay valley IRSP6 LISS-IV satellite imagery.

### Limitations

The most serious obstacle of such hydrological analysis is the non-availability of data for longer period (e.g. >25 years) and this limits the confidence in design floods

**Table 3** Summary of GOF results for selected probability distributions fitted to Ajay River discharge data ( $Q_{max}$ ) ( $n = 25$ )

| Sl. no. | Distributions                | Kolmogorov–Smirnov (K–S) |      | Anderson–Darling (A–D) |      | Chi squared ( $\chi^2$ ) |      |
|---------|------------------------------|--------------------------|------|------------------------|------|--------------------------|------|
|         |                              | Statistic                | Rank | Statistic              | Rank | Statistic                | Rank |
| 1.      | Gumbel (EV-I)                | 0.1298                   | 3    | 0.59007                | 4    | 0.94511                  | 3    |
| 2.      | Weibull (EV-III)             | 0.12795                  | 2    | 0.45666                | 1    | 3.7042                   | 4    |
| 3.      | Log-normal (LN)              | 0.13612                  | 4    | 0.57134                | 3    | 0.80735                  | 2    |
| 4.      | Log-Pearson Type III (LPT-3) | 0.12333                  | 1    | 0.47792                | 2    | 0.30034                  | 1    |

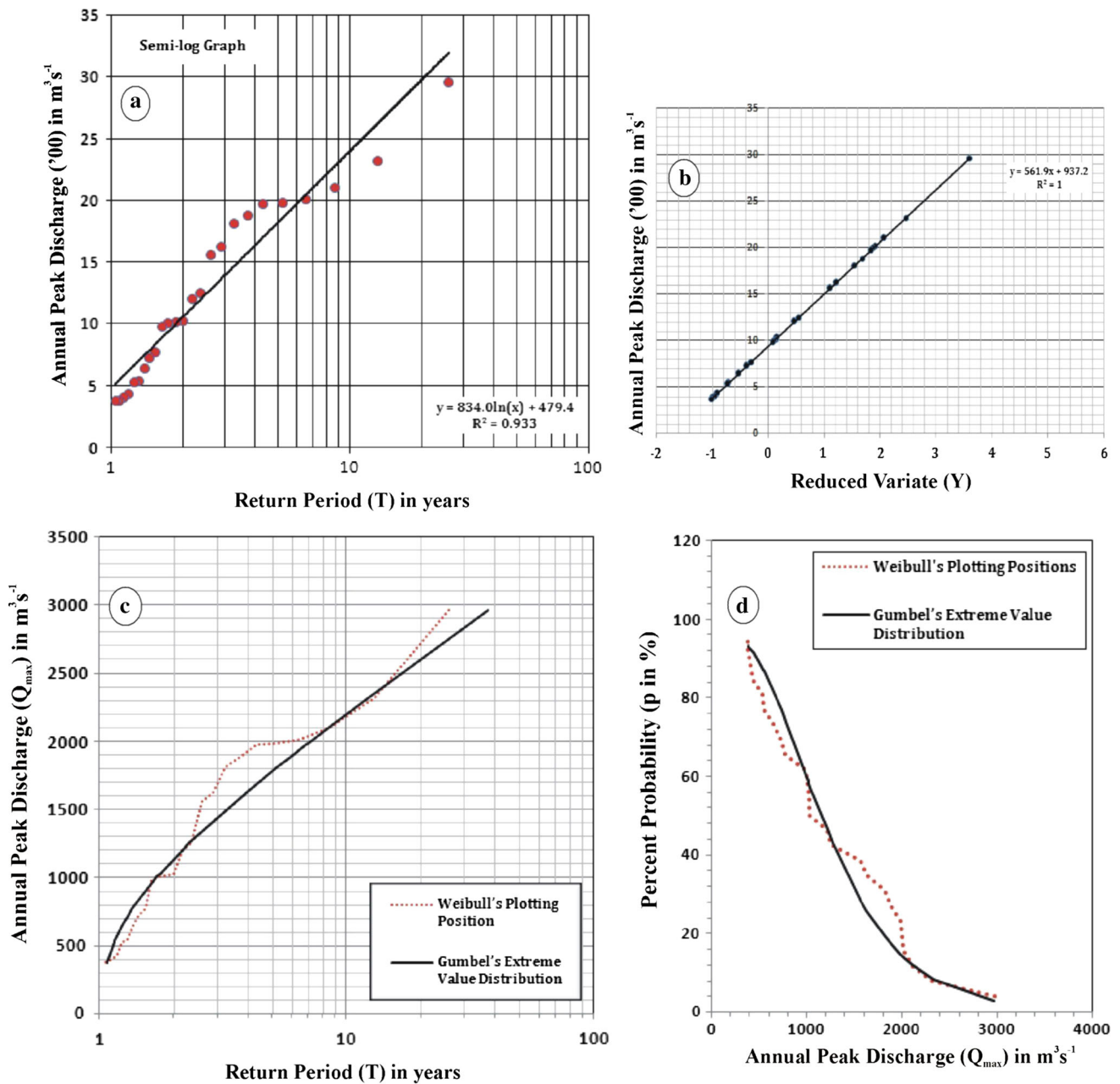
estimated using data from a single site, particularly when using shorter record lengths and when estimating design values for longer return periods (e.g. 100 years). Further, these analyses incorporate assumptions of a high degree of accuracy in the estimation of discharges at each stage of the modelling process. But, it is known that considerable error is introduced in measurement in the instrumental record (Kidson and Richards 2005). In the light of geological evidences, the major climatic changes have occurred over time scales involving thousands of years and longer. So, the stationarity assumption and the procedures of long-term extrapolation based only on a relatively short instrumental record are likely to be erroneous (Knox and Kundzewicz 1997).

**Results and discussion**

Flood frequency analysis using different methods has been carried out on the annual maximum flood series ( $Q_{max}$ ) of Ajay River at Nutanhat for the period of 1985–2009. The ranked discharge data reveal that there are a greater number of discharge data below the mean discharge of  $1146.769 \text{ m}^3 \text{ s}^{-1}$  than those above it and the variations above the mean of the annual peak discharge data are greater than those below the mean (Fig. 3c). Hence, the Weibull’s plotting of return year ( $T$ ) against the  $Q_{max}$  on the semi-log graph (Fig. 7a) is a skewed curve that bends towards the tails of the data. It happens so because the distribution of extreme value observations depends upon the tails of the frequency distribution from which the observations are drawn. After Weibull’s method (EV-III), return period ( $T$ ) of flood like the highest peak discharge of the year 1999 ( $2964.234 \text{ m}^3 \text{ s}^{-1}$ ) is 26 years and the lowest flood magnitude of the year 1998 ( $375 \text{ m}^3 \text{ s}^{-1}$ ) is 1.04 years and the corresponding percent probability are 3.85 and 96.15 % respectively. Analysis reveals that except the first three ranked discharge data, the plotted points lie near to a straight line. The other probability approaches including EV-I (Fig. 7b), LN and LPT-3 using frequency

factor ( $K$ ) have been applied to peak flow recorded at Nutanhat. From EV-I (Gumbel’s probability distribution), it has been estimated that the most probable annual flood of  $375.072 \text{ m}^3 \text{ s}^{-1}$  discharge has a recurrence interval of 1.071 i.e., likely to occur once in every year with an exceedence probability of 93.37 %. Comparison between EV-I and EV-III depicts that for the larger annual events, the EV-III method gives lower  $T$  value. It can easily be observed and interpreted from Fig. 7c that return period ( $T$ ) of a particular observed flood flow is more appropriate in EV-I method than EV-III because it gives a near-linear relationship. Further insight into Fig. 7d shows the near-linear relation between discharge ( $\text{m}^3 \text{ s}^{-1}$ ) and percent probability distribution in case of EV-I. The floods corresponding to different return period’s 5-, 10-, 25-, 50-, 100-, 200-, 500- and 1000-year are also estimated using EV-I, LN, LPT-3 in order to assess the vulnerability of lower ARB in future under a given hydrologic situation. The results (Fig. 8) of computed peak flows ( $X_T$ ) show relatively higher magnitude of computed peak discharges corresponding to different return periods as observed in case of LPT-3 compared to the other two methods. The slightly higher discharge obtained by LPT-3 (Table 4) points towards a more vulnerable situation of this area in upcoming years. The computed flood magnitude ( $X_T$ ) of 5- and 200-year return period is estimated as 1779.521 and  $3913.086 \text{ m}^3 \text{ s}^{-1}$  respectively by EV-I method. However, the LN distribution shows the discharge of 1800.114 and  $5400.078 \text{ m}^3 \text{ s}^{-1}$  for 5- and 200-year return periods, respectively.

As revealed from the different figures and postulations above for flood frequency measures, it is germane to compute the extent of uncertainty and assess the fitness of the data for the prediction of affected area at different return periods ( $T$ ) in future and accordingly proper inundation maps must be prepared. For the assessment on fitting of probability distributions to recorded and computed  $Q_{max}$  data series, GOF test statistics for four distributions were computed and given in Table 3. The results of K–S and  $\chi^2$  tests showed LPT-3 distribution appears to be the most appropriate fit among four



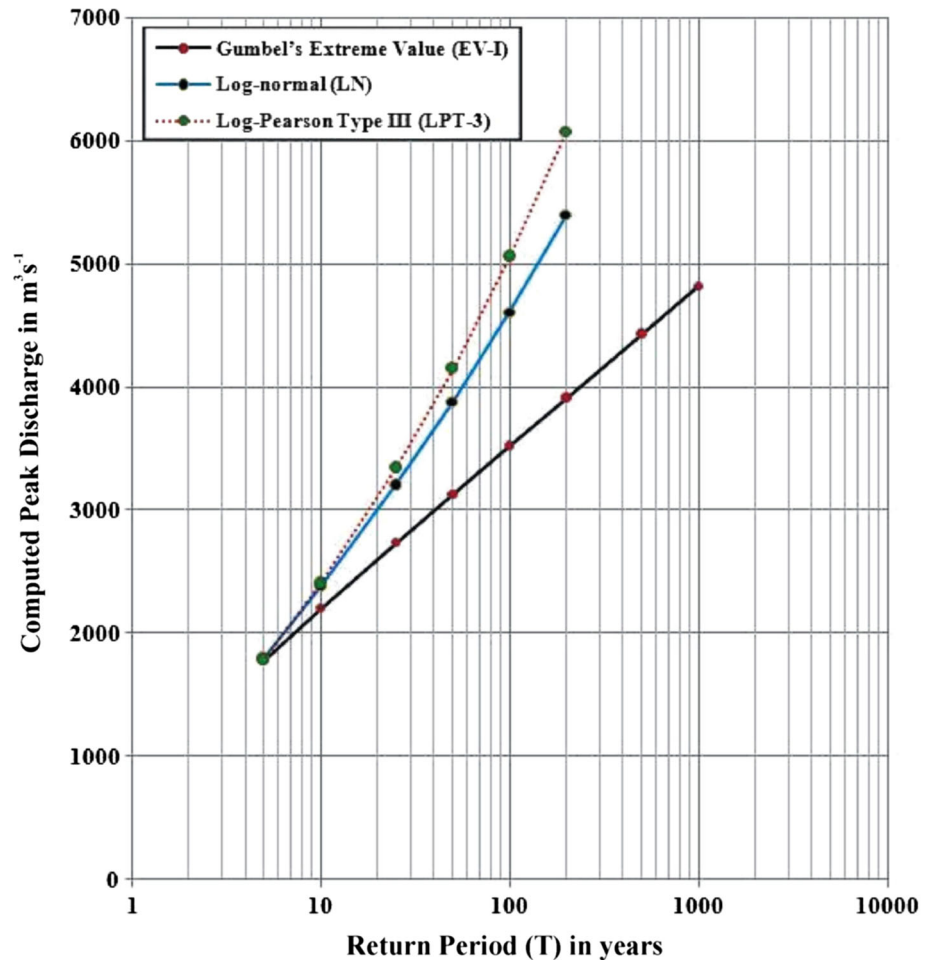
**Fig. 7** **a** Weibull’s probability plot illustrating the different return period with corresponding river discharge annual maximum series (1985–2009) for the River Ajay. **b** Variate graph of Gumbel’s extreme value distribution for the River Ajay based on the 1985–2009 record of  $Q_{max}$  at Nutanhat. **c** The relationship of return period and

corresponding discharges manifests the comparison between the empirical distribution of Weibull’s method and Gumbel’s extreme value. **d** Comparison between the flood probability of Weibull’s and Gumbel’s method

probability distributions. But the LPT-3 showed to fit the second best probability distribution in A–D test. With the objective of confirmation, *D*-index test has been employed to assess the adequacy of suitable probability distribution for the data under study. The respective index value is lower for the LPT-3 distribution (0.424). It is thus concluded that the more suitable one for analysing the flood data of Ajay River is LPT-3 distribution. Hence,

LPT-3 is accepted as the principal measure for computing gauge height (base flood) with specific return period and inundation area mapping was done from this base flood results. The estimated gauge data showed that a 21.12 m gauge level with the probability (*P*) of 1 % in Ajay River is expected to occur in every 100 years (Table 5). On the otherhand, a 19.65 m gauge level has a 50 % *P* to occur in every 2-year return period which cross the bankfull

**Fig. 8** Plots of estimated peak discharge ( $X_T$ ) using EV-I, LN and LPT-3 distributions. Vulnerability has been assessed in future for the flood affected areas of Ajay Basin from this graph



**Table 4** Discharge-frequency analysis of Ajay River for various design return period using LPT-3 distribution

| Return period ( $T$ ) | Skew co-efficient ( $\beta_1$ ) | Frequency factor, $K$ (frequency factor table) | $\delta_{\log X}$ | $K \cdot \delta_{\log X}$ | $\log \bar{X}$ | $\log X_T$ | $X_T$    |
|-----------------------|---------------------------------|--|-------------------|---------------------------|----------------|------------|----------|
| 5                     | 0.26                            | 0.830  | 0.275             | 0.22825                   | 3.024          | 3.25225    | 1787.516 |
| 10                    |                                 | 1.301  |                   | 0.35777                   |                | 3.38177    | 2408.629 |
| 25                    |                                 | 1.818  |                   | 0.49995                   |                | 3.52395    | 3341.566 |
| 50                    |                                 | 2.159  |                   | 0.59372                   |                | 3.61772    | 4146.866 |
| 100                   |                                 | 2.472  |                   | 0.6798                    |                | 3.7038     | 5055.918 |
| 200                   |                                 | 2.763  |                   | 0.75982                   |                | 3.78382    | 6078.830 |

stage (19.19 m) and maximum safe level (DL) at Nutanhat.

**Vulnerability studies and recommendations**

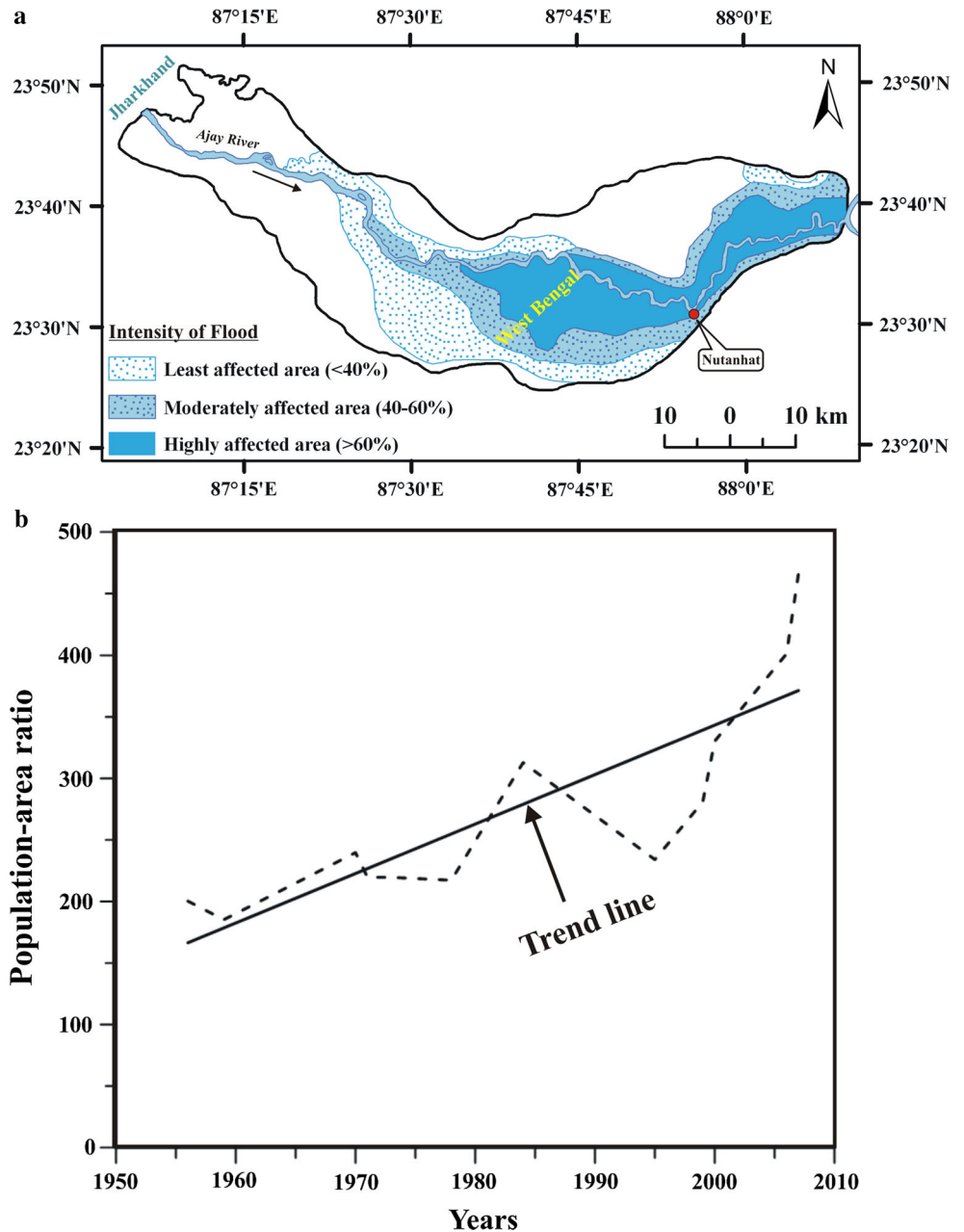
Annual variation of floods is quite variable and unpredictable in the area under study. As people are not normally prepared to face the floods, the damage becomes quite severe. To study the flood vulnerability, a flood affected

zonation map (Fig. 9a) of the basin in West Bengal based on the data supplied by Department of Irrigation and Waterways, Govt. of West Bengal is prepared. It is seen that most of the chronically inundated and highly flood affected zones fall on the low-lying land than their surroundings which is close to the river. As discussed earlier, the runoff co-efficient is low (<0.3) with flat topographic slope (0.4°–0.6°) in these zones which indicate the most vulnerability to flooding condition. These low-lying areas are normally affected by the floods of the Ajay and its

**Table 5** Computed peak gauge height ( $X_T$ ) at different return periods ( $T$ ) and area inundated for 25- and 200-year  $T$  using LPT-3 method

| Return period ( $T$ ) | Probability ( $P$ ) of occurrence (%) | $\log \bar{X}$ | $\delta_{\log X}$ | Skew co-efficient ( $\beta_1$ ) | $X_T$ (gauge height in meters) | Area affected (km <sup>2</sup> ) |
|-----------------------|---------------------------------------|----------------|-------------------|---------------------------------|--------------------------------|----------------------------------|
| 10                    | 10                                    | 1.295          | 0.009             | 1.058                           | 20.37                          | –                                |
| 25                    | 4                                     |                |                   |                                 | 20.7                           | 235.985                          |
| 50                    | 2                                     |                |                   |                                 | 20.89                          | –                                |
| 100                   | 1                                     |                |                   |                                 | 21.12                          | –                                |
| 200                   | 0.5                                   |                |                   |                                 | 21.31                          | 286.513                          |

**Fig. 9 a** Flood intensity map showing areas susceptible to flood. Extent of flood prone areas based on flood affected areas from 1956 to 2007 (Source: Department of Irrigation and Waterways, Govt. of West Bengal). **b** The year-to-year variation in the ratio between flood affected-population and the flood-affected area (in km<sup>2</sup>) between 1956 and 2007





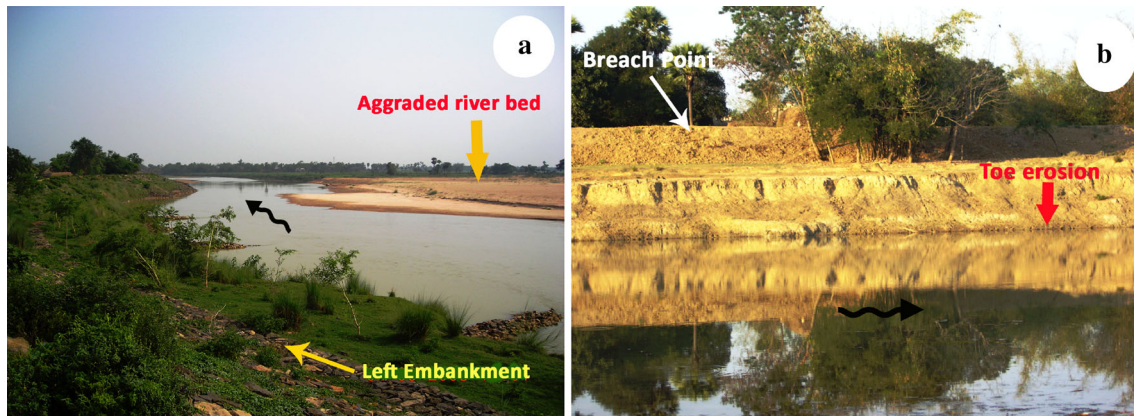
tributaries; i.e. Kunur and Kandor and also due to breaching of embankments of the Ajay River. The zones far from active channels with higher slope are occasionally inundated and least flood affected. In the recent decades, the flood affected area increases temporally from 1985 to 2009, i.e. the affected area of 305.72 km<sup>2</sup> during 1984 increased to 1488.85 km<sup>2</sup> in 2000 along with a simultaneous increase in gauge height to 23.21 m. In addition, from FMA using LPT-3 method, the lower ARB is also vulnerable to floods for the return period of 25-, 50-, 100- and 200-year (Table 4), which can bring colossal loss to people and property in future. The spatial extent of inundated area for 25- and 200-year return periods within the basin is estimated and given in Table 5 and there is a clear affiliation of inundation of 235.985 km<sup>2</sup> adjacent to Nutanhat during the next 25 years. This area will increase to 286.513 km<sup>2</sup> in the next 175 years. A two-dimensional (2-D) flood inundation mapping is also adopted for this study based on the outcome of the flood frequency measures and the subsequent GOF. The 2-D flood inundation map of the basin with 25-year return period (Fig. 11a) indicates the inundation of 8.4 % area of total lower ARB.

It is observed that while the area affected by floods has varied and increased, the population affected by floods has remarkably increased. This is clearly indicated by the population-area ratio graph and the trend line (Fig. 9b). But this is surprising considering the facts that the peak discharge ( $Q_{max}$ ) of all the floods except that of the 1999 flood did not exceed the discharge (2408.629 m<sup>3</sup> s<sup>-1</sup>) of 10-year return period with probability of 10 %. However, the Ajay overtopped the EDL (~20.19 m) 10 times (Fig. 3d) during the major flood years (1959–2009). The computed peak gauge height of 19.65 m cross the DL at Nutanhat only for the 2-year return period ( $P = 50$  %). Therefore, in the light of above discussion, the logical explanations for the increased inundation area are the (a) increasing trend in the Gangetic West Bengal monsoon rainfall (Kumar et al. 2010) and (b) the remarkable haphazard increase of settlements in the flood prone areas which reduces the water-carrying capacity of the river. Further, the vulnerability to population is increased due to the significant increase of the concentration of population. During field investigation, it has been also found that the channel of the River Ajay at Nutanhat (at confluence with Kunur River) aggraded continuously (Fig. 10a) that decreased the channel slope that forced the water to overtop the banks. On the otherhand, the poor structural flood control measures (embankment) have aggravated the flood problems in this area due to variability (co-efficient of variation = 51 %) of peak annual discharge (Fig. 3b). The floodplain undergoes great changes as a result of the confinement of river flow due to construction of embankment. Confinement increases stream power that facilitates sediment entrainment (erosion

from bed and banks) within the river system which leads to devastating breaching of embankment (Fig. 10b). The breach results in large area floods than natural spilling (without embankment) and subsequent sand incursion in the fertile and populated floodplain. The flood plain is not only deprived of the rich silt laden water, but also the carried materials are forced to be deposited within the river channel. As a result, the river bed rises very sharply compared to the surrounding areas and makes the embankments more vulnerable for future. This, in other words, implies that the problem of flooding and flood vulnerability has risen exclusively due to anthropogenic causes. These observations have important implications for flood management programmes.

On the basis of these analyses, probable flood management measures are suggested:

1. It appears that excess and haphazard development and rapid population growth in the valleys and floodplains have primarily resulted in increased vulnerability of population to flood hazards. As more and more people populate flood-prone areas, the potential for damage from flood increase. Hence, it is necessary to take concrete measures to stop further population growth and development activity in the floodplains of lower ARB and enforce the law to properly regulate such developmental activity.
2. The landuse characteristics of floodplain under the influence of flood are taken into consideration for mitigation. It indicates that the physical and socio-economic conditions are liable for the increase of a region's susceptibility to disaster. That is to say, a flood of same exceedence probability will have levels of vulnerability and damage according to the landuse characteristics. The vulnerability studies, therefore, consist of identifying the appropriate land use and its zonation. Appropriate landuse zoning (Fig. 11b) matched carefully with the intensity of flood hazard is needed with an aim to maximize the outputs from the floodplain and minimizing the risks and consequences of flood i.e. keeping people away from the water.
3. Through a proper study of the basinal equilibrium parameters (stream power, sediment load etc.), appropriate planning could be made to control the flood waters (Bandyopadhyay et al. 2014). Due to high runoff co-efficient and severe soil erosion in the hilly upper catchment, high sediment load gets incorporated in the channel at various points that creates an unstable situation of Ajay River. It has been estimated that incorporated sediment contributes about 15 % of the total load (Niyogi 1987) and about 25 % of the total bed load is contributed by Bhagirathi during rainy



**Fig. 10** **a** Field photograph in June 2008; illustrates rising river bed very sharply due to the construction of concrete embankment (rock rip-rap) for reducing flood vulnerability. **b** Ground check at Teora village, Bardhaman district in February 2009: it is showing the effect

of flood of the monsoon season i.e. breaching of earthen embankment even after 2 years. During flood season the water level raises up to the embankment level (seen on the *upper right* of the *photograph*)

season (Basumallick and Mukherjee 1999). So, limited dredging should be carried out to increase the water-carrying capacity of the river and to prevent back flow from Bhagirathi River.

4. Flood emergency measures such as flood forecasting, evacuation and recovery plans are needed for reducing flood hazard by modifying the responses of the population at risk i.e. increase the flood mitigation awareness of the people.

Further, the constructions of embankments do solve the problem of flooding temporarily but, at the same time, they give a false sense of security to the people living nearby. In many areas of lower ARB, a large population actually lives near the embankments. This often results in a heavy loss of life and property in case of embankment breach. The best choice of man would be to identify, demarcate and delineate the flood plain boundary from the satellite imageries and leave it to the channels (Bandyopadhyay and Jana 2010). It should be prohibited for any type of construction and permanent settlements.

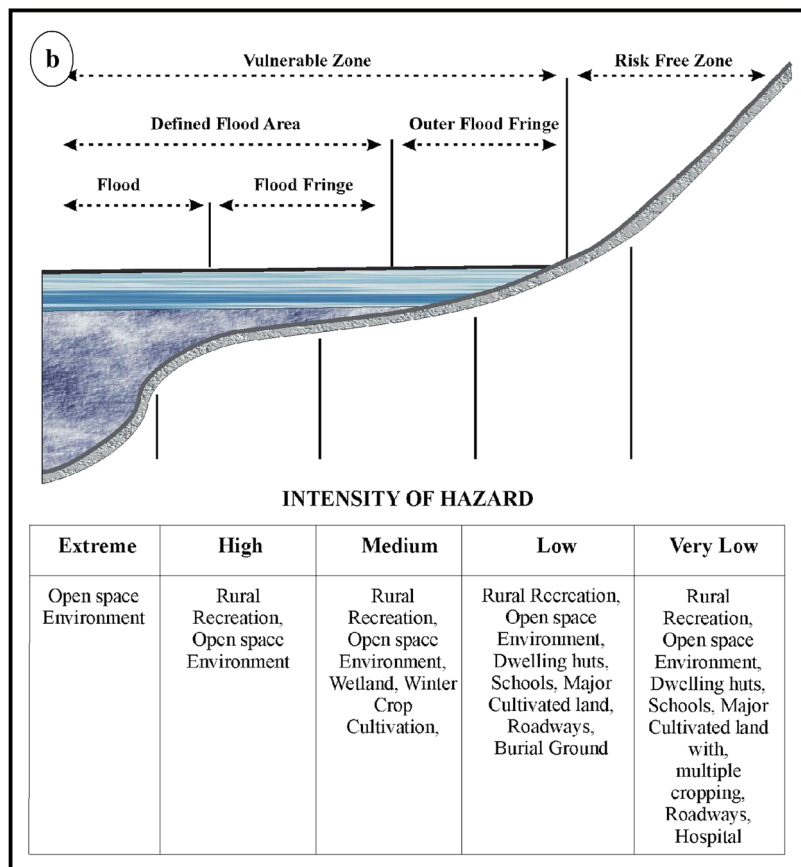
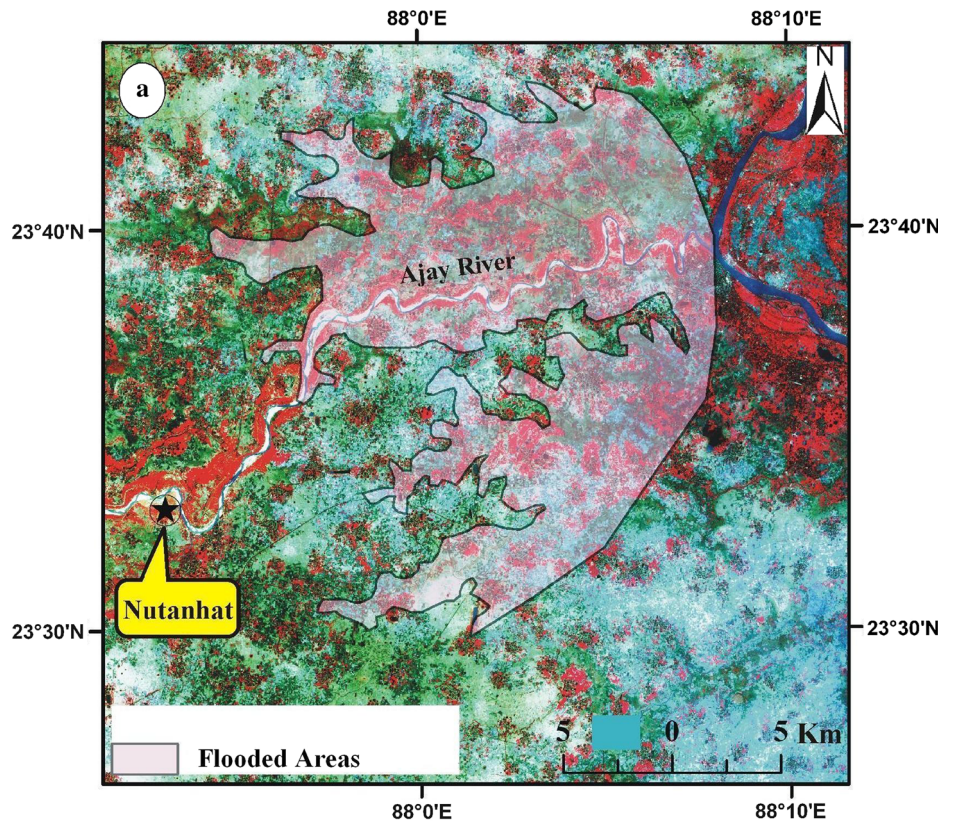
## Conclusion

Unpredictability of flood behaviour is rapidly undergoing into absolute uncertainty in eastern India. Intense and extreme rainfalls are making the floodways of all rivers vulnerable to greater floods (Valdiya 2011). In this context, flood assessment and monitoring is crucial for environmental sustainability, particularly within areas traversed by river floodplain. The current study is an effort to provide an effective planning tool for flood plain managers and administrators. Frequency-magnitude analysis (FMA) is carried out for Nutanhat in the lower part of ARB and the

various forms of probability distributions have been tested in order to find the best fitting distribution for vulnerability studies. The GOF and *D*-index tests revealed that the LPT-3 distribution is appropriate for future vulnerability analysis of this river. The magnitude and probability of occurrence of flood peaks of specified return periods is estimated using LPT-3 distribution which would be very much helpful to cope with such peaks. FMA of stage data combined with GIS of the likely inundated areas of 25- and 200-year return periods has been estimated. The analysis shows that there will be the likelihood of an increased flood affected area in future. In addition, the inundation areas are mapped using the 25-year return period gauge height and DEM. Therefore, the combination of the two results would be a step forward for flood management and mitigation strategies. Such an approach would provide a synoptic view of the importance of the landuse and population distribution regulation through flood plain zoning in order to prevent damages. As the area is a lowland floodplain, proper landuse zoning will go a long way in reducing flood damages in areas frequently invaded by flood waters.

However, floods have occurred in the past and will continue to occur in future as well. It is neither possible to totally stop floods nor to completely eliminate the flood damages. In spite of, the present analyses provide some important clues to minimize the severity of the impact and the damage potential of the flood hazard. River-friendly and multi-pronged measures that are based on the scientific understanding of the cause and effects of floods and that recognize the geomorphic importance and environmental value of floods are likely to be more effective measures of flood control than the structural measures (Kale 1998, 2004). Actually, it must be realized that floods are part of the natural river process. They become a hazard when human interference with river dynamics causes unwanted inundation and consequent loss

**Fig. 11** **a** 25-year return period flood inundation in lower ARB, especially around Nutanhat based on computed gauge height is remarkable on the IRSP6 LISS-IV image (path/row—107/055) of January 2014. **b** Appropriate landuse zoning in the lower ARB (based on Floodplain Management in Australia: Best Practice Principles and Guidelines 2000 with slight modification and addition)



of life and property. Therefore, in the long run, a shift in paradigm is must from the current emphasis on ‘flood control’ to ‘flood management’.

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