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Flash flood susceptibility assessment using the parameters of drainage basin morphometry in SE Bangladesh

Akhtar Alam[1]*, Bayes Ahmed[1], Peter Sammonds[1]

[1]Institute for Risk and Disaster Reduction, University College London, Gower Street, London, WC1E 6BT, United Kingdom.

*Corresponding author: AA (akhtar.alam@ucl.ac.uk)

Abstract

Predicting the occurrence and spatial patterns of rainfall induced flash floods is still a challenge. Instant genesis and typically smaller areal coverage of the flash floods are the major impediments to their forecasting. Analysis of the morphometric parameters provides useful insight on hydrological response of the drainage basins to high intensity rainfall events. This information is valuable for understanding the flash flood potential of the drainage basins and for evading the destructions caused by the hazard. Here, we use eighteen morphometric parameters that influence the runoff volume, flow velocity, and inundation depth scenario of a flash flood. The analysis has been carried out for simulating the relative flash flood susceptibility of thirteen watersheds (B1 to B13) of variable sizes in southeastern Bangladesh. The morphometric parameters were derived from Digital Elevation Model (DEM) using Geographic Information System (GIS). The evaluated basin parameters include: area (A), perimeter (P), length (Lb), stream order (Su), stream number (Nu), stream length (Lu), stream frequency (Fs), drainage density (Dd), texture ratio (Rt), bifurcation ratio (Rb), basin relief (Hr), relief ratio (Rr), ruggedness number (Rn), time of concentration (Tc), infiltration number (If), and form factor (F). Two relative flash flood susceptibility scenarios were generated: (i) general watershed level, and (ii) more precise pixel level status. The watershed level comparison reveals that B4 and B6 watersheds constituting 72.61% of the total area are 'very high' susceptible, whereas the

susceptibility of the other watersheds has been found as 'high' [B5 (6.95%)], 'moderate' [B8 and B13 (8.63%)], 'low' [B2, B10, B11 (4.64%)], and 'very low' [B1, B3, B7, B9, and B12 (7.18%)]. The derived watershed susceptibility map was subsequently integrated with two spatial analysis algorithms i.e., topographic wetness index (TWI) and topographic position index (TPI) through overlay analysis. The integration helped to understand the combined role of the general watershed morphometry and the in situ topography for determining flash flood susceptibility of each spot (30m x 30m) within all the selected watersheds. The quantitative analysis and characterization of the watersheds from the perspective of flash flood hazard in this investigation is expected to be useful for implementing the site-specific mitigation measures and alleviating the effects of the hydrological hazard in the study area.

Keywords: basin; drainage; flash floods; morphometry; Bangladesh; Remote sensing; GIS

1. Introduction

Flash floods are among the world's deadliest natural hazards, accounting for 85% of flooding, having the highest mortality rate with more than 5,000 lives lost annually (www.wmo.int). Bangladesh is one of the most flood prone countries in the world experiencing almost all types of flooding. Having a long history of the hydrometeorological disasters, the country has witnessed a huge clustering of the extreme flood events in close space and time. The most devastating flood events of 1953, 1954, 1955, 1956, 1962, 1963, 1966, 1968, 1969, 1970, 1971,1974, 1976, 1984, 1987, 1988, 1997, 1998, 2000, 2004, 2007 and 2012 are examples of the series from the 20th and beginning of the 21st century (Khalil, 1990; Dewan et al., 2003; Choudhury and Haque, 2016; Philip et al., 2019). The impact of the most recent monsoon flood in 2019 has also been widespread, effecting 2.1 million people in 24 districts and killing 104 people (BRCS, 2019; www.dhakatribune.com). On an average floods inundate 20.5% area of the country annually to as high as about 70% during an extreme flood event, primarily because of the low-lying topography and location of the country at the confluence of three major rivers i.e., Ganges, Brahmaputra and Meghna (Mirza, 2002). The floodplains of these rivers constitute about 80% area of the country; however, more than 90% of the catchment area of these rivers is outside Bangladesh (Brammer, 1990).

Flash floods, although affecting relatively lesser area (5-20%), result in substantial loss of human lives, property, and livelihoods especially in the mountainous parts of the country (Kamal, 2018). In a recent flash flood of August 2014, around 0.81 million people were affected, including 0.5 million displaced, and thousands of hectares of crops lost (ACAPS, 2014). This was immediately followed by another flash flood in June 2015, hitting southeastern parts of the country; Cox's Bazar, Bandarban, and Chittagong districts were severely affected by this flash flood in which 22 persons were killed and 1.8 million people effected (HCTT, 2015). Another high intensity rainfall triggered flash flood was experienced during April 2017; the breaching of embankments from this event resulted in inundation of extensive cropland mainly in six northern districts and effected more than 4.6 million people (Tarannum, 2018). A heavy downpour in June 2018 recorded over 300 mm of rain in just 48 hours destroying hundreds of Rohingya refugee shelters in the Cox's Bazar district (www.floodlist.com).

Flash floods are mostly of convective origin, occurring locally in watersheds of less than 1000 km^2 with complex orography and short response times of few hours or minutes; thus, allowing minimum possibilities for the prediction (Marchi et al., 2010; Destro et al., 2018). Usually taking place in ungauged watersheds, flash floods are the least documented phenomenon of the hydrometeorology (Gaume et al., 2009). While, torrential rainfall remains the main reason behind the occurrence of the flash floods, watershed morphometry is an important factor influencing the intensity of the hazard. Characterizing the morphometric properties of the catchments provide a valuable insight about their hydrological response (e.g., flash flood) to rainfall events (Borga et al., 2008).

The classic works of Horton, 1932 and 1945, Smith, 1950; Strahler 1952, Miller, 1953 and Schumm, 1956 have long been used as a guide for such studies. In the recent years, quantitative analysis of the morphometric properties [linier, areal, and relief] of the basin through the application of mathematical measures has been widely performed for multiple purposes especially for assessing flood hazard potential of the drainage basins (e.g., Mesa, 2006; Angillieri, 2008; Ozdemir and Bird, 2009; Romshoo et al., 2012; Bhatt and Ahmed, 2014; Abuzied et al., 2016; Farhan et al., 2015; Fenta et al., 2017; Bhat, 2019, Adnan et al., 2019).

Remote sensing data products and Geographic Information System (GIS) have often been integral part of the studies performing spatial assessment of various natural hazards and other processes operating on the earth (Alam et al., 2018, 2019b; Ahmed et al., 2020). Freely available the digital elevation models (DEMs) such as Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Advanced Land Observing Satellite (ALOS) in combination with GIS have been particularly used for drainage basin morphometric analysis (e.g., Reddy et al., 2004; Romshoo et al., 2012; Altaf et al., 2013; Bhatt and Ahmed 2014; Farhan et al., 2015; Adnan et al., 2019; Bhat et al., 2019, Meraj et al., 2019).

Quantitative morphometric analysis of the selected basins in the present study is particularly important because the basins are ungauged and there is lack of information on their past hydrological behavior. Accordingly, with the combined use of digital elevation data (SRTM) and GIS, this study attempts to evaluate eighteen discharge, flow velocity, and inundation influencing morphometric parameters i.e., area (A), perimeter (P), length (Lb), stream order (Su), stream number (Nu), stream length (Lu), stream frequency (Fs), drainage density (Dd), texture ratio (Rt), bifurcation ratio (Rb), basin relief (Hr), relief ratio (Rr), ruggedness number (Rn), time of concentration (Tc), infiltration number (If), form factor (F), topographic wetness index (TWI) and topographic position index (TPI) for assessing the flash flood susceptibility of the selected watersheds/basins.

2. Study area

The area of interest is located between 21º00′0″ – 21º60′0″ N and 92º05′0″ – 92º35′0″ E in the southeastern Bangladesh. (Fig 1). The total area of the selected site is 3170 km², spread over the parts of multiple *Upazilas* in three districts i.e., Cox's Bazar [Chakaria, Cox's Bazar-S, Ramu, Ukhia and Teknaf] Bandarban [Alikadam, Naikhongchhari and Lama], and relatively small part of Chittagong [Banshkhali]. The area is composed of 13 watersheds/basins (B1, B2,..B13) with sizes ranging from16.8 km² (B11) to 1525.4 km² (B4) and being a coastal area elevation stretches from 0 to 889 meters above mean sea level. The eastern segment of the study area encompasses high mountainous, with steep slopes and higher drainage density (see Fig 2 for general geomorphic properties of the area). Surface geology of the region consists of beach and dune sand (Coastal sediments), valley alluvium and colluvium, Dihing and Dupi Tila Formation, Dihing Formation (Pleistocene and Pliocene), Tipam Sandstone (Neogene), Boka Bil Formation (Neogene) and Bhuban Formation (Miocene) (GSB, 1990). The geomorphic signatures are evocative of NW-SE trending geological structures controlling the watercourses e.g., the trunk channel in the watershed B4 of the study area. Rainfall in the area exhibits a specific spatial pattern; the southern watersheds receive relatively higher mean annual rainfall than the northern watersheds (Fig. 2e). The area is often experiencing the flash floods and consequent losses especially during the monsoon season; the most recent events have been those of 2015 and 2018. It important to note that in addition to the native population, there are 209,847 Rohingya refugee families with a population of 909,774 (UNHCR, 2019) temporarily settled in the watershed B9, B10, B11, and B13 (since August, 2017), who now become the prey of the flash floods (e.g., in 2018). The refugees are living in makeshift tarpaulin and bamboo shelters spread over the multiple clusters in Ukhia and Teknaf *Upazilas* of the Cox's Bazar district. Given the occurrence of varied natural hazards including cyclones, landslides and floods (Ahmed et al., 2018; Alam et al., 2019) and social, economic and demographic conditions, the refugees seem to be the most at-risk community in the study area.

3. Materials and methods

Quantitative analysis of the morphometric parameters has long been used to understand the nature and origin of the drainage basins (Horton 1945, Smith, 1950; Strahler 1952, Miller, 1953 and Schumm, 1956). The morphometric characteristics considerably impact the hydrological behavior of the catchments; consequently, number of previous investigations have been carried out in relation to the flood hazard. Drainage basin morphometry can play a substantial role in the occurrence and intensity of the flash floods (Fig 3). Over the period of time, morphometric parameters have been widely used for understanding the relationship; however, there is no defined or standard set of the morphometric parameters that may be used for flash flood susceptibility analysis (Adnan et al., 2019). In most of the previous studies, the results obtained through the process of morphometric analysis tend to be generalized, where discharge generating potential or response to rainfall events is projected relatively between the various watersheds without the identification of hazard-hotspots. The deliverables of such studies are of limited use from the perspective of flood hazard mitigation. For that reason, the present study adopted a two-step approach to assess the flash flood susceptibility of the study area. The 1st step aims to understand relative flood hazard scenario of the watersheds by deriving the values of each selected morphometric parameter through the application of different mathematical procedures (Table 1, serial no.1 to 16). For a consistent comparison, the derived values of the chosen morphometric parameters corresponding to each watershed were subsequently converted to new common evaluation scale of 1-5; on this scale the flood susceptibility increases from 1 to 5. According to the nature of a particular parameter (+ or – relationship with the flood susceptibility), a new value was assigned to each parameter of all the watersheds. Finally, a cumulative value was used to project the flash flood susceptibility of each watershed in the form of a map. The 2nd step was the integration of final flood susceptibility map with two other wetness and surface flow sensitive topographic parameters (Table 1). The two-step approach provided the opportunity to: (i) identify comparative flood hazard of different watersheds and (ii) pinpointing the exact spots within the watersheds displaying higher levels of flash flood susceptibility. The process involved the conversion of all the data layers into raster format, with consistent projection (WGS 1984, UTM Zone 46 N) and cell size (30m x 30m). The use of SRTM digital elevation model (30m) and GIS has been fundamental aspect of this analysis.

4. Results and discussion

4.1 Morphometric parameters

The basic morphometric characteristics including area (A), perimeter (P) length (Lb), and elevation (m) of the delineated watersheds are presented in the Table 2; and the quantitative analysis of the other parameters and their flash flood connotations are discussed under the respective headings.

4.1.1 Stream order (Su)

The classification of the streams according to number of stream segments (1st, 2nd, 3rd …) and type of confluence (1st with 1st, 2nd with 2nd, 3rd with 3rd…) is a measure of stream ordering (Strahler, 1957). Su is a fundamental indicator of the size of a drainage basin and discharge capacity. In this analysis watershed B4 and B6 have the highest order of streams (VI), whereas the watersheds including B1, B3, B11, B12, and B13 are with III as the highest order stream (Table 3 and 4). High stream order of B4 and B6 represents presence of larger streams in the catchments fed by multiple small streams, thus having the potential of high water discharge and depending on the relief conditions high flow velocities as well.

4.1. 2 Stream number (Nu)

Stream number is the count of streams of different orders in a given drainage basin or a watershed (Strahler, 1957). The watersheds having high stream numbers usually cause high runoff and rapid peak flow during rain storm events than the basins with low Nu (Bhat el al., 2019). The stream number was found to be highest (1934) in watershed B4 (Table 5, Fig 4) followed by B6, B5, and B8 with 950, 260 and 215 respectively. All the remaining watersheds show Nu of less than 200 with lowest being that of the B11 watershed (25), suggesting least runoff capacity.

4.1.3 Stream length (Lu)

Lu refers to the length of streams of different orders in a basin. Stream length is one of the important characteristics of surface runoff; larger Lu is an insinuation of less infiltration and high runoff producing ability of a drainage basin (Strahler, 1952). Lu and Nu are positively related i.e., watersheds with high Lu have high Nu value as well and are thus proxy representatives of each other. As expected from the size of the watershed, B4 revealed highest (1943.93) Lu, followed by B6 (954.64), B8 (302.73), and B5 with 280.03. Similar to the pattern of the Nu, rest of the watersheds have Lu lower than 200 (Table 5 and Fig 4).

4.1.4 Stream Frequency (Fs)

The count of stream segments of all orders per unit area is referred to as stream frequency. High Fs implies high runoff delivery, which is generally a function of impermeable surface material, sparse vegetation cover, and high relief (Patton and Baker, 1976; Reddy et al., 2004). The Fs of the watersheds ranges from 0.80 as lowest for the watershed B9 to 2.33 as highest for the watershed B5 (Table 5, Fig 4); remaining watersheds reveal the intermediate values of the stream frequency.

4.1.5 Drainage Density (Dd)

The spacing between the channels is called as drainage density (Horton, 1932). Dd is calculated as the total length of channels of all orders per unit area divided by the area of a drainage basin. High drainage density is an important indicator of high runoff volumes and rapid flood peaks (Horton, 1932; Patton, 1988; Pallard et al.2009). High Dd is often associated with impermeable soils, sparse vegetation, and mountainous terrain. In this analysis drainage density was found to be highest in watershed B5 with a value of 2.51 (Table 5, Fig 4), thus is likely to produce high runoff; whereas, the Dd values for other watersheds ranges from 1.07 (B3) to 1.37 (B7).

4.1.6 Texture ratio (Rt)

Representing the ratio between total number of streams and perimeter of a basin, the texture ratio (Rt) is a function of lithology, slope, climate, vegetation, and soil type and is classified into four types i.e., coarse (< 4 per km), intermediate (4–10 per km), fine (10–15 per km), and very fine (> 15 per km) (Smith, 1950). The Rt for the watershed B4 and B6 reveal intermediate values of 7.48 and 5.62 respectively, thus suggesting higher quick peak discharge generation potential (Table 5, Fig 4). The remaining watersheds express coarser texture with lowest being that of watershed 12 with 1.02.

4.1.7 Bifurcation ratio (Rb)

Rb is a dimensionless measure representing the ratio between the number of stream segments of any order (Nu) and the next higher order (Nu+1). This is a very important parameter that expresses the degree of ramification of the drainage network (Mesa, 2006). Bifurcation ratio is usually minimum in flat or rolling drainage basins and higher in mountainous or dissected drainage basins (Horton, 1945). Here, the mean bifurcation ratio of the watershed B4 has been observed to be highest (6.09), followed by the B13, and B6 with 4.9 and 4.39 correspondingly. The watershed B1 exhibited a minimum Rb value of 0.67 (Table 5, Fig 4). The high Rb suggests a basin having high runoff generation potential with relatively minimum lag for triggering the flash flooding during torrential rains (Chorley 1969; Howard, 1990).

4.1.8 Basin relief (Hr)

Basin relief is the difference in elevation between the lowest and highest points in a basin (Schumm 1956). Basin relief is an important indicator of denudation, landform evolution, and runoff of a watershed (Patton, 1988). Hr also explains the gradient of the streams, slope steepness and precipitous discharge delivery (Hadley and Schumm 1961). The watershed B4 (889), B6 (629), B8 (384) and B13 (244) have the high basin relief value connoting higher probability of the flash floods than other watersheds with Hr of less than 100 (Table 5 and Fig 4).

4.1.9 Relief Ratio (Rr)

Rr is a ratio of basin relief or total relief to horizontal distance along the longest dimension of the basin parallel to the principal drainage line (Schunm, 1956). Relief ratio allows comparisons of relative relief in basins regardless of differences in scale of topography (Costa, 1987). Rr provides an idea about the flow velocity, slope steepness, and erosion status of a drainage basin. The Rr of the watersheds varies from 21.98 (highest) for B13 to 3.34 (lowest) for B7 (Table 5 and Fig 4). The high Rr indicates reduced lag time, sudden peak discharge, and high probability of flash flooding (Patton, 1988).

4.1. 10 Ruggedness number (Rn)

Ruggedness number is the dimensionless product of drainage density and relief (Costa, 1987). Rn is high in the basins with steep long slopes, favoring erosion, quick peak flows and flash floods (Patton and Baker, 1976). A ruggedness < 1 means flat topography; a value of 1–2 indicates undulating topography, and extreme values (> 2) indicate 'badland' topography (Adnan et al., 2019). Watershed B4 has a highest ruggedness number of 1.125 and the number is less than one in all other watersheds (see Table 5 and Fig 4).

4.1. 11 Time of concentration (Tc)

Time parameters such as time of concentration, the time to peak, and the lag time are important considerations in flood hydrology (McCuen et al., 1984). The time of concentration is the maximum time required for water to travel from the most distant point of the watershed to outlet. Tc is a fundamental parameter to calculate the peak discharge potential of a watershed. With inverse relationship, the larger values of the Tc imply lower probability of sudden peak flows. The Tc of the watershed B4 and B6 has been calculated as 57 and 31 respectively (Table 5 and Fig 5). For all other watersheds Tc is less than 30 (calculated after Kirpich, 1940).

4.1.12 Infiltration number (I_f)

The infiltration number is a function of the D_d and F_s. It is an important parameter to understand infiltration potential of a watershed. Higher the I_f, lower will be the infiltration and the higher runoff (Bhatt and Ahmed, 2014). The I_f is lowest in watershed B9 with a value of 0.96, suggesting relatively minimum infiltration, whereas the value is highest (5.84) for the watershed B5 (see Table 5 and Fig 5).

4.1.13 Form factor (F_f)

Form factors is expressed as a ratio between the area of the basin and the square of the basin length (Horton, 1932). Form factor is a parameter to predict the flow intensity of a watershed; the high F_f values indicate high discharge of short duration and vice versa (Gregory and Walling, 1973). The watershed B11 is having the highest form factor value of 0.645, followed by the B8 an B3 with 0.500 and 0.426 respectively (Table 5 and Fig 5).

4.1.14 Topographic Wetness Index (TWI)

TWI is used to calculate topographic control on wetness and runoff (Schmid and Persson, 2003; Sørensen et al., 2006, Wu et al., 2016). Runoff generation can be modelled using the topographic wetness index; the part of a catchment where the wetness index exceeds some threshold is assumed to be saturated (Woods and Sivapalan, 1997). The index allows the delineation of a portion of the watersheds potentially exposed to flood inundation or flash flooding (Risi et al., 2018). In this analysis TWI values range form 1-9, where 1 represents least likelihood of inundation and 9 highest. Although, all the watersheds share a substantial area with high TWI values, the maximum of the area with high TWI values were observed in the watershed B4, B6, B7 and B8.

4.1.15 Topographic Position Index (TPI)

TPI compares the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell (Weiss, 2001). Positive TPI values indicate that the central point is located higher than its average surroundings, while negative values indicate a position lower than the average; TPI is increasingly used to measure topographic slope positions and to automate landform classifications (Reu et al., 2013). Here, we make use of TPI to identify ridges, peaks, flat areas and topographic depressions. Choosing a threshold of -8.10 to 9.59, we identify the areas where probability of waterlogging is relatively high. In general, the steep mountainous parts of the watershed B4, B6 and B8 have least potential to cause topographic inundation than the low relief areas of the other watersheds.

4.2 Flash flood susceptibility mapping

On the basis of cumulative value derived through the adopted methodology, this analysis reveals that B4 and B6 have the high discharge generating potential and are most susceptible to flash floods than the remaining watersheds. The watersheds are spread over 1525.4 km² (B4) and 774.9 km² (B6), which collectively constitutes 72.61% of the total area (Fig 6a). The morphometric parameters such as stream number (Nu), stream length (Su), texture ratio (Rt) mean bifurcation ratio (Rb), basin relief (Hr), relief ratio (Rr) and ruggedness number (Rn) with values of 1934, 950 (Nu), 1943.93, 954.64 (Lu), 7.48, 5.62 (Rt), 6.09, 4.39 (Rb), 889, 629 (Hr), 9.19, 12.21 (Rr), and 1.125, 0.725 (Rn) for the watershed B4 and B6 respectively have been decisive in determining their 'very high' flash flood susceptibility. The watershed B5 reveals 'high' susceptibility (6.95%), followed by B8, and B13 with 'moderate' levels of the susceptibility (8.63%). Watershed B2, B10, B11 exhibit 'low' (4.64%); while as, the remaining watersheds that include B1, B3, B7, B9 and B12 express comparatively least 'very low' susceptible (7.18%) to the flash floods (Fig 6a).

Combining the watershed level susceptibility scenario (Fig 6a) with in situ TWI and TPI results (Fig 6b, c) through the procedure of weighted overlay analysis in GIS allowed to precisely depict the flash flood susceptibility of each spot (30x30m pixel) in all the watersheds (Fig 7). The detailed quantification of the area under various flash flood susceptibility classes in each watershed is presented in Fig 8.

In general, all the communities in the study area are exposed to the varying degree of flash flood hazard; but those in the high susceptibility zones of different watersheds have higher probability of being effected. Coincidentally, larger part of the high susceptibility areas in these watersheds is uninhabited and pose limited threat, except the western parts of Chakaria and Cox's Bazar-S. However, given the vulnerability factors such as high population density and fragile nature of the makeshift settlement (Fig. 9), the Rohingya refugees even if located in largely low susceptible watersheds (B9, B10, B11, and B13) seem to be at higher risk of the flash floods. Because of the relatively less rugged terrain and low elevation of the hills in these watersheds, the Rohingya refugee settlements may not be impacted by the high velocity flows but the likelihood of getting inundated during the flash floods is relatively high.

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5 Conclusion

Each year rainfall induced flash floods cause huge loss of life and property across the globe. Recognizing the flash flood potential of the drainage basins is important for reducing the associated damages. In this study, multiple morphometric parameters effecting runoff volume, flow velocity, and water depth were evaluated for understanding the flash flood susceptibility of thirteen watersheds in SE Bangladesh. The morphometric parameters were derived from the digital elevation model using GIS. The results reveal that watershed B4 and B6 would be more responsive to high intensity rainfall events and may generate larger and instant discharge, suggesting that the watersheds are more susceptible to flash floods than the remaining watersheds considered for this analysis. In addition to general watershed scale morphometric characteristics, consideration of the local topographic effects helped to precisely map the flash flood susceptibility in all watersheds, which also describes the uniqueness of this study. However, vertical accuracy of the basic data set used i.e., 30m SRTM DEM (RMSE = 8.28m) is a major concern here that restricts practical application of the produced results at a scale demanding finer details. Moreover, validation of the derived flood hazard scenarios remained unperformed because of the insufficient historical record of the flash floods. It is also pertinent to point out that flash flood hazard is not entirely a function of morphometric conditions; therefore, the scenarios may change owing to the influence of other factors such as land use/cover and flood management practices in each watersheds and hydraulic structures along the channels. Furthermore, the factors like soil saturation and debris load, though not within the scope of the present analysis are important factors that influence discharge, flow velocity and severity of the flash floods. Despite the limitations and uncertainties of the data and adopted methods, the deliverables of this study hold substantial value for understanding flood hydrology and developing the flood mitigation policy for the study area.

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Table 1 Morphometric parameters selected for the present analysis

S. No.	*Parameter*	*Mathematical expression*	*Reference*
1	Basin area (A) km²	A = the entire area from drainage divide to outlet point	Schumm, 1956
2	Perimeter (P) km	P = the perimeter is the total length of the drainage basin boundary	Schumm, 1956
3	Basin length (L_b) km	L_b = the basin length corresponds to the maximum length of the basin measured parallel to the main drainage line	Schumm, 1956
4	Stream order (S_u)	Hierarchical = classification of streams based on the number and type of tributary junctions	Strahler, 1952
5	Stream number (N_u)	N_u = N1 + N2 + …+Nn	Strahler, 1952
6	Stream length (L_u)	L<u>u</u> = L1 + L2 + …+Ln	Strahler, 1952
7	Stream frequency (F_s)	$F_s = Nu/A$ where, Nu = total number of stream segments of all orders, and A = basin area.	Horton, 1945
8	Drainage density (D_d)	$Dd = Lu/A$ where, Lu = total length of all the ordered streams, and A = area of the basin.	Horton, 1945
9	Texture ratio (Rt)	Rt = Nu/P where, Nu = total number of stream in a given basin, and P = perimeter of the basin	Smith, 1950
10	Bifurcation ratio (R_b)	$R_b = Nu/Nu$+1 where, Nu number of streams of any given order, Nu+1 the number in the next higher order	Horton, 1945
11	Basin relief (H_r)	$H_r = Hmax - Hmin$ (m) where $Hmax$ is the highest and $Hmin$ the lowest point of the basin	Schumm, 1956
12	Relief ratio (R_r)	$R_r = Hr/L$ R_r is the dimensionless height–length ratio between the basin relief (R) and the basin length (L)	Schumm, 1956
13	Ruggedness number (R_n)	$Rn = Dd \times (\mathrm{Br}/1000)$ where, Br = basin relief Dd = drainage density	Melton, 1957
14	Time of concentration (T_c)	$T_c = G\ k\ (L / S^{0.5})^{0.77}$ where, G = Constant (G=0.0078) k = Kirpich adjustment factor L = Longest watercourse length in the watershed S = Average slope of the watercourse	Kirpich, 1940
15	Infiltration number (I_f)	$I_f = F_s \times D_d$ where, F_s is stream frequency the and $_{Dd}$ drainage density	Faniran, 1968

16	Form factor (F)	$F = A/L^2$ where, A area of the basin and L^2 the squared basin length	Horton, 1932
17	Topographic Wetness Index (TWI)	TWI = ln (a/tanβ), Where, a is the specific catchment area (SCA): the local upslope area draining through a certain point per unit contour length, which is equal to a certain grid cell width, and β is the local slope	Beven and Kirkby, 1979
18	Topographic Position Index (TPI)	$TPI_i = M_0 - \sum_{n-1} \frac{M_n}{n}$ where, M_0 = elevation of the model point under evaluation, M_n = elevation of grid, n = the total number of surrounding points employed in the evaluation.	Guisan et al., 1999; Weiss, 2001

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Table 2 Basic morphometric attributes of the selected watersheds

Basin	Area (km^2) (A)	Perimeter (km) (P)	Length (km) (L_b)	Elevation (m) Min (h)	Elevation (m) Max (H)

B1	26.6	27.5	12.0	1	98
B2	92.4	48.7	15.5	1	97
B3	28.0	32.8	8.1	1	47
B4	1525.4	258.3	96.7	0	889
B5	220.4	85.2	25.8	0	108
B6	774.9	169.0	51.5	0	629
B7	93.0	71.5	22.4	0	75
B8	233.4	93.5	21.6	0	384
B9	61.9	48.5	17.3	0	75
B10	38	33.9	11.2	0	73
B11	16.8	20.4	5.1	1	70
B12	18.1	25.4	8.0	0	57
B13	40	35.5	11.1	0	244

Table 3 Stream order (Su) and Stream number (Nu) of the watersheds

Basin	I	II	III	IV	V	VI	Total
B1	20	11	7	0	0	0	38
B2	73	37	26	6	0	0	142
B3	24	11	5	0	0	0	40
B4	1113	537	265	14	4	1	1934
B5	173	73	10	3	1	0	260
B6	612	299	29	7	2	1	950
B7	78	36	7	1	0	0	122
B8	173	29	10	2	1	0	215
B9	39	8	2	1	0	0	50
B10	35	17	1	0	0	0	53
B11	15	9	1	0	0	0	25
B12	17	8	1	0	0	0	26
B13	35	23	1	0	0	0	59

Basin	I	II	III	IV	V	VI	Total
B1	13.78	7.1	9	0	0	0	29.88

B2	58.93	32.98	21.33	4.38	0	0	117.62
B3	14.92	11.2	3.97	0	0	0	30.09
B4	980.77	495.44	230.17	118.77	62.43	56.35	1943.93
B5	138.74	63.77	59.9	13	4.62	0	280.03
B6	467.23	256.33	115.66	85.57	[illegible]	26.95	954.64
B7	64.79	33.58	14.39	14.67	0	0	127.43
B8	154.89	75.05	49.35	21.06	2.38	0	302.73
B9	36.96	16.48	19.78	2.11	0	0	75.33
B10	24.41	15.23	9.07	0	0	0	48.71
B11	11.9	6.57	2.38	0	0	0	20.85
B12	15.58	4.99	3.43	0	0	0	24
B13	23.94	17.23	3.7	0	0	0	44.87

Watershed	Stream number (Nu)	Stream length (Lu)	Stream frequency (Fs)	Drainage density (Dd)	Texture ratio (Rt)	Mean bifurcation ratio (Rb)	Basin relief (Hr)	Relief ratio (Rh)	Ruggedness number (Rn)	Time of concentration (Tc)	Infiltration number (If)	Form factor (F)

Table 4 Stream length of all the orders (Su) in each watershed

B1	38	29.88	1.42	1.12	1.38	0.67	97	8.083	0.097	12	1.59	0.184
B2	142	117.62	1.53	1.27	2.91	1.54	96	6.19	0.104	16	1.94	0.384
B3	40	30.09	1.42	1.07	1.21	0.87	46	5.67	0.033	10	1.51	0.426
B4	1934	1943.93	1.26	1.27	7.48	6.09	889	9.19	1.125	57	1.60	0.163
B5	260	280.03	2.33	2.51	3.05	3.19	108	4.18	0.381	27	5.84	0.167
B6	950	954.64	1.22	1.23	5.62	4.39	629	12.21	0.725	31	1.50	0.292
B7	122	127.43	1.31	1.37	1.70	2.86	75	3.34	0.086	28	1.79	0.185
B8	215	302.73	0.92	1.29	2.29	3.17	384	17.77	0.443	13	1.18	0.500
B9	50	75.33	0.80	1.21	1.03	2.17	75	4.33	0.082	20	0.96	0.206
B10	53	48.71	1.36	1.25	1.56	3.81	73	6.51	0.082	12	1.7	0.310
B11	25	20.85	1.48	1.24	1.22	2.13	69	13.5	0.080	5	1.83	0.645
B12	26	24	1.43	1.32	1.02	2.02	57	7.12	0.027	9	1.88	0.282
B13	59	44.87	1.47	1.12	1.66	4.9	244	21.98	0.256	7	1.64	0.323

Table 5 Derived values of all the morphometric parameters for each watershed

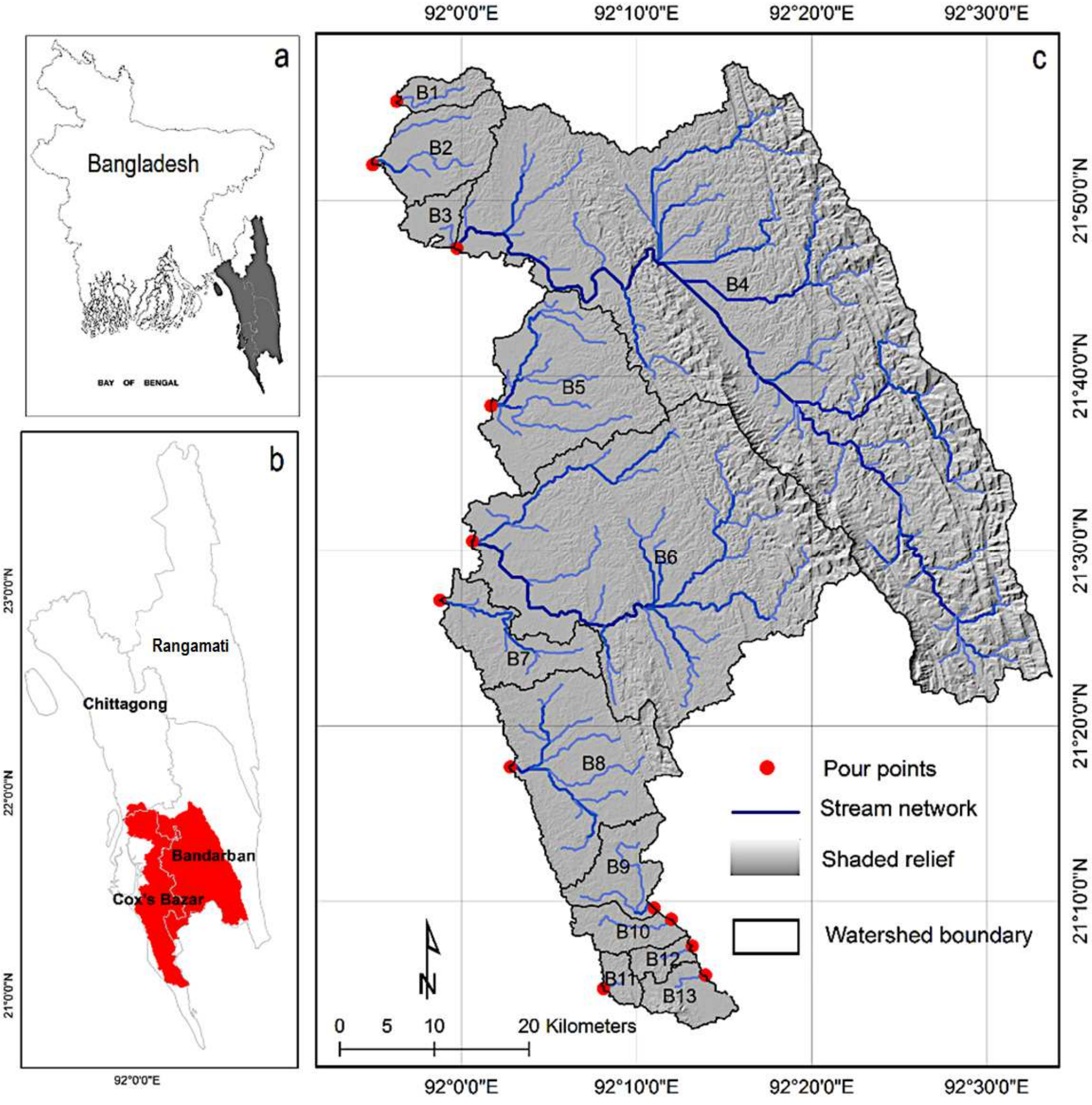

Fig 1 a. Location of the study area in Bangladesh, b. spatial extent of the site in relation to neighbouring sub-districts, and c. shaded relief showing the selected watersheds, drainage divide, major streams and pour point of each watersheds.

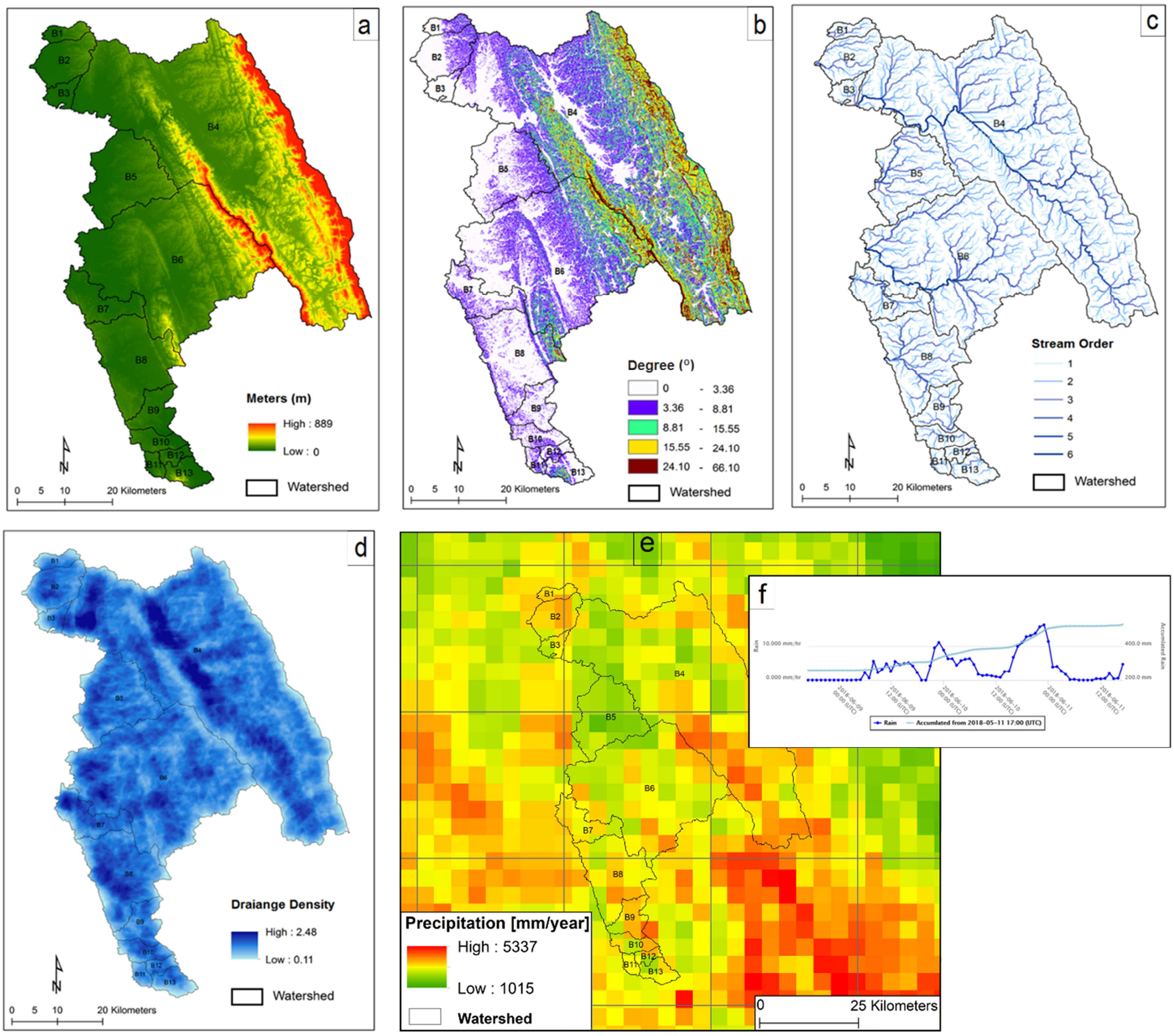

Fig 2 General physical characteristics of the selected watersheds; a. digital elevation model (SRTM 30m), b. slope (º), c. stream order, d. drainage density, e. precipitation pattern [Tropical Rainfall Measuring Mission (TRMM)] and f. rainfall [Global Rainfall Map (GSMaP)] of June 2018 flash flood.

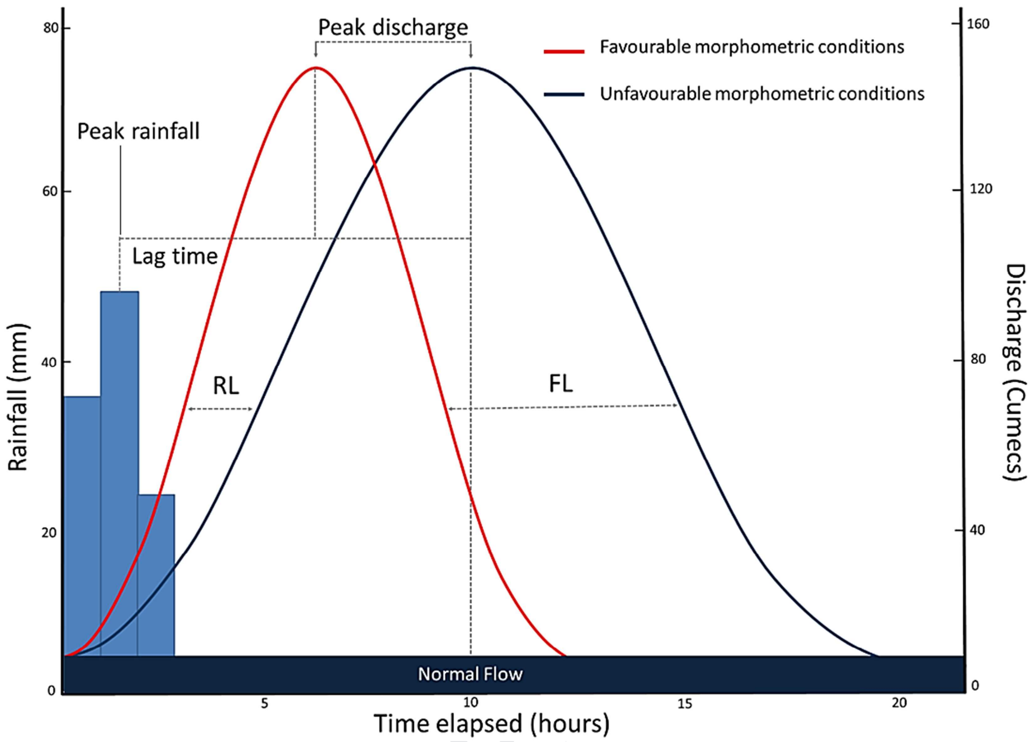

Fig 3 Hydrograph illustrating the general effect of drainage basin morphometry on peak discharge; RL: rising limb, FL: falling limb.

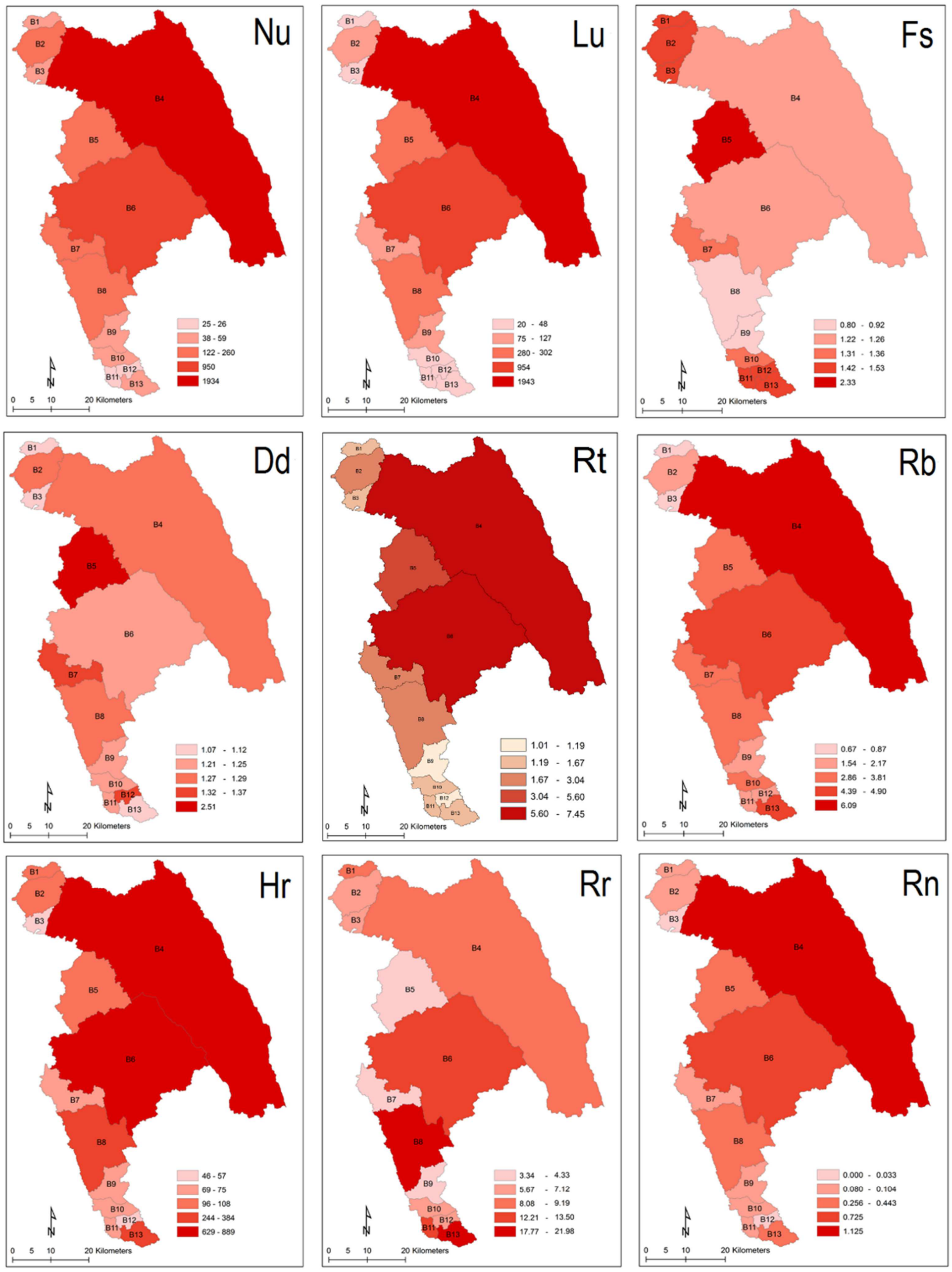

Fig 4 Morphometric parameters; stream number (Nu), stream length (Lu), Stream frequency (Fs), drainage density (Dd), texture ratio (Rt), bifurcation ratio (Rb), basin relief (Hr), relief ratio (Rr), and Ruggedness number (Rn).

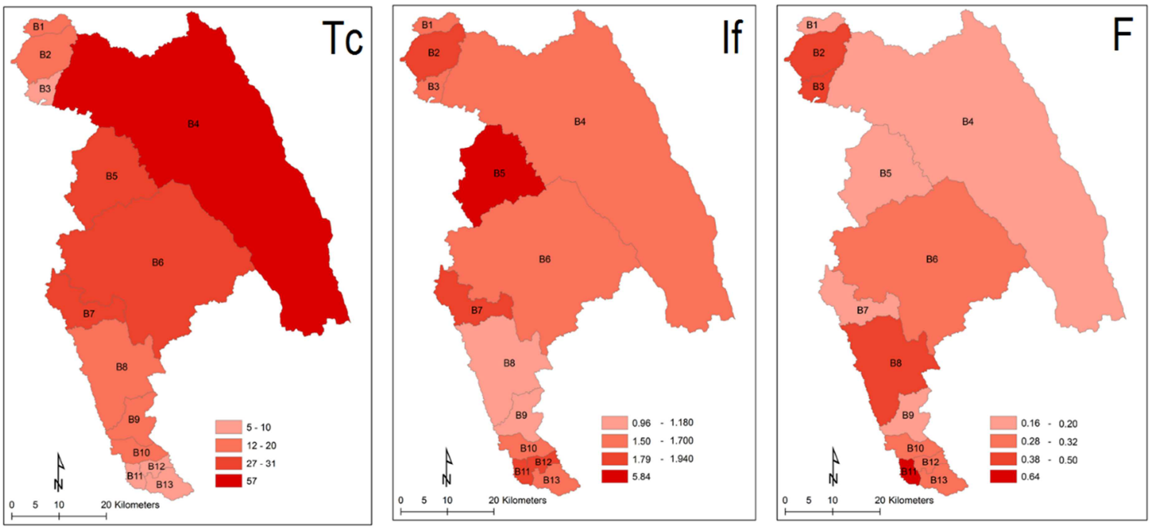

Fig 5 Morphometric parameters; time of concentration (Tc), infiltration number (If), and form factor (F).

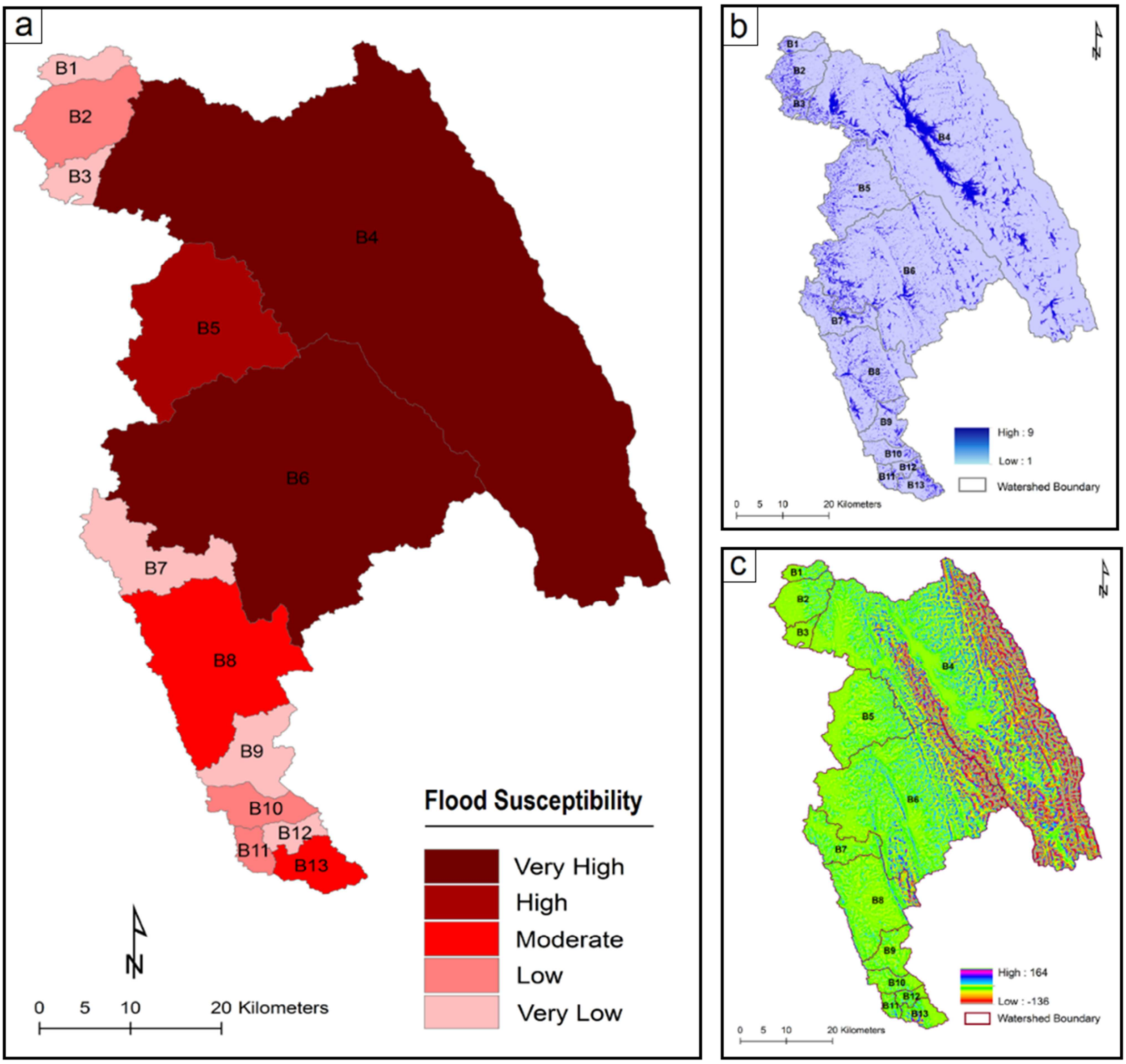

Fig 6 a. Relative flash flood susceptibility of the watersheds, b. topographic wetness index (TWI), c topographic position index (TPI).

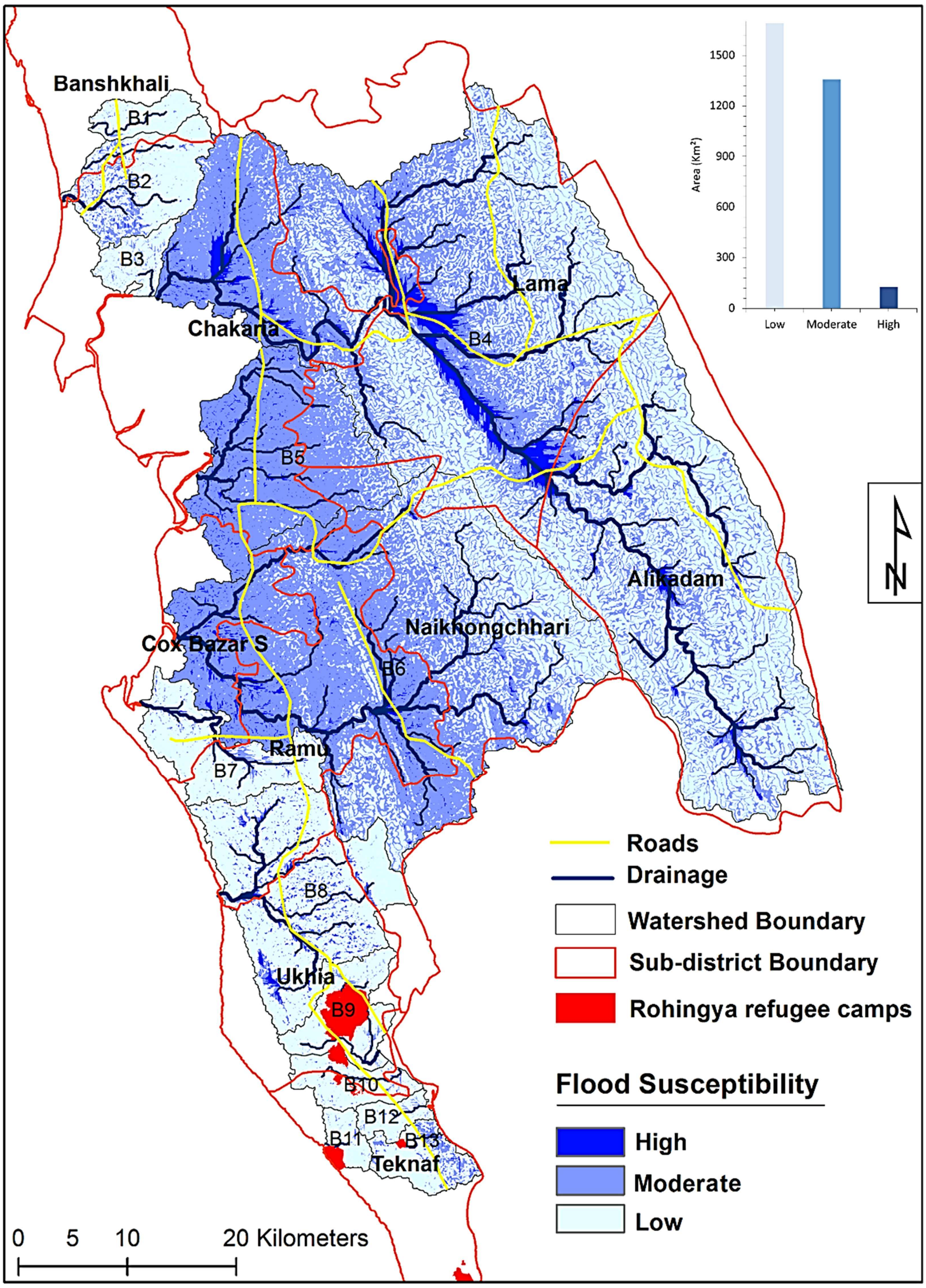

Fig. 7 Precise flash flood susceptibility scenario of all the locations in each watershed.

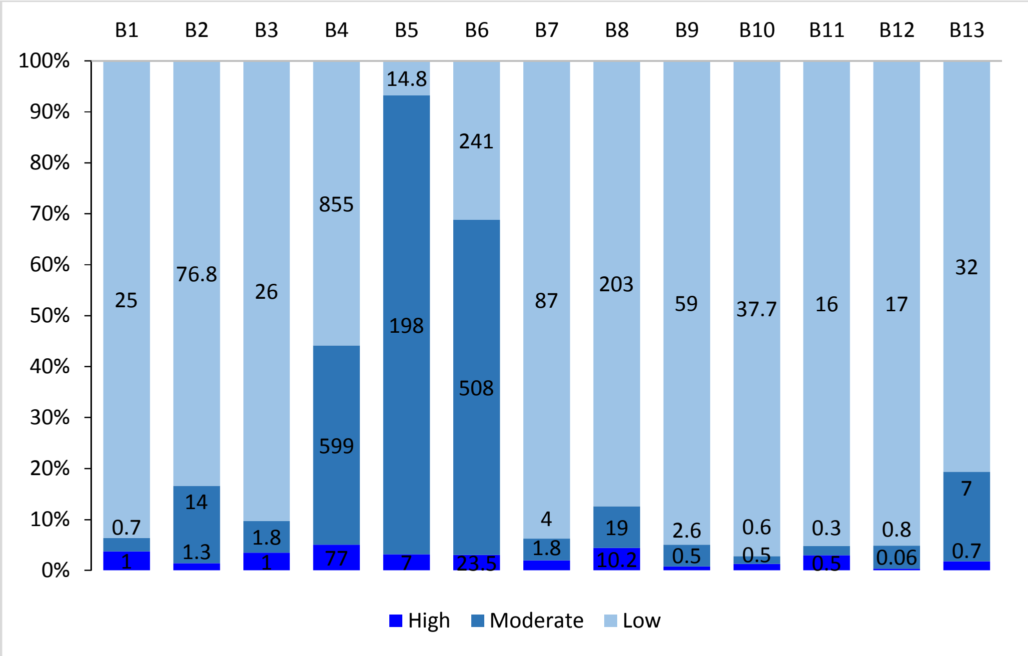

Fig 8 Area under various flash flood susceptibility classes in each watershed (B1-B13); figures are in square kilometers.

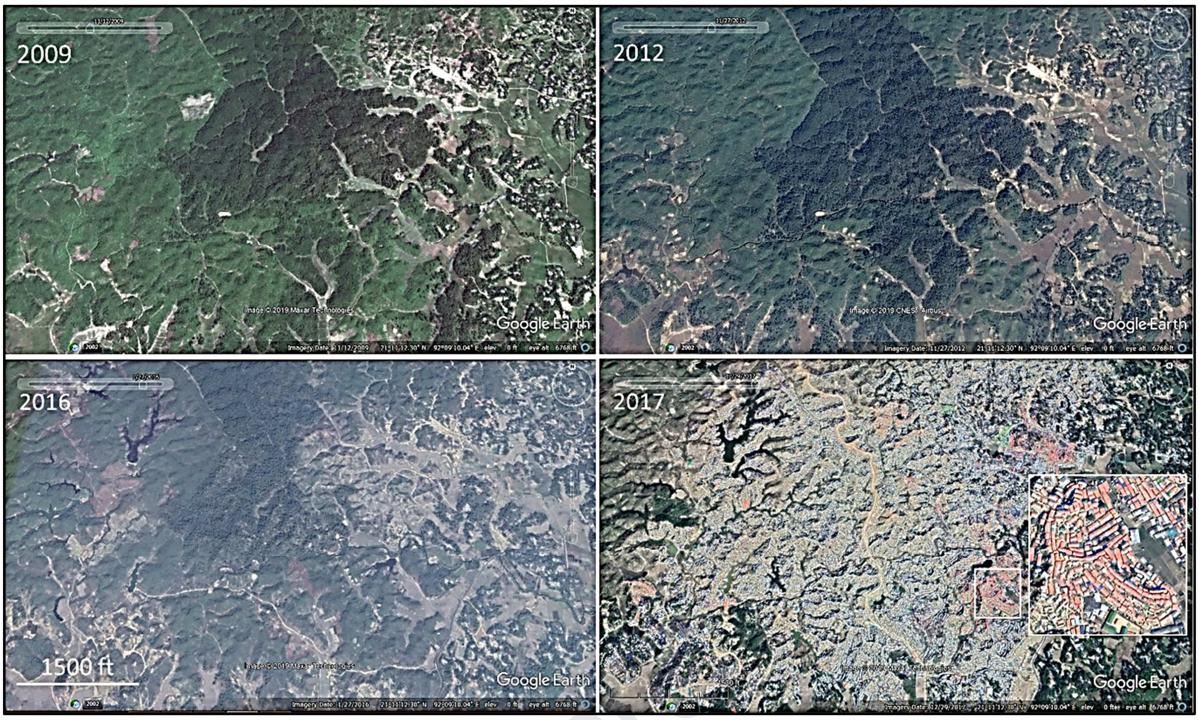

Fig. 9 Google Earth images showing the enormous land transformation in the B9 watershed of the study area as result of Rohingya refugee influx from Myanmar; the inset on the 2017 image shows the zoomed view of a part of the Kutupalong refugee camp.

Conflict of Interest

The authors declare no conflict of interest.

Akhtar Alam
On behalf of all authors