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The use of watershed geomorphic data in flash flood susceptibility zoning: a case study of the Karnaphuli and Sangu river basins of Bangladesh

Abstract

The occurrence of heavy rainfall in the south-eastern hilly region of Bangladesh makes this area highly susceptible to recurrent flash flooding. As the region is the commercial capital of Bangladesh, these flash floods pose a significant threat to the national economy. Predicting this type of flooding is a complex task which requires a detailed understanding of the river basin characteristics. This study evaluated the susceptibility of the region to flash floods emanating from within the Karnaphuli and Sangu river basins. Twenty-two morphometric parameters were used. The occurrence and impact of flash floods within these basins is mainly associated with the volume of runoff, runoff velocity, and the surface infiltration capacity of the various watersheds. Analysis showed that major parts of the basin were susceptible to flash flooding events of a 'moderate' to 'very high' level of severity. The degree of susceptibility of ten of the watersheds was rated as 'high', and one was 'very high'. The flash flood susceptibility map drawn from the analysis was used at the sub-district level to identify populated areas at risk. More than 80% of the total area of the 16 sub-districts were determined to have a 'high' to 'very high' level flood susceptibility. The analysis noted that around 3.4 million people reside in flash flood prone areas, therefore indicating the potential for loss of life and property. The study identified significant flash flood potential zones within a region of national importance, and exposure of the population to these events. Detailed analysis and display of flash flood susceptibility data at the sub-district level can enable the relevant organizations to improve watershed management practices and, as a consequence, alleviate future flood risk.

Keywords: Flash flood; watershed hydrology; morphometric analysis; geomorphology; GIS; Bangladesh

1. Introduction

The flash flooding phenomenon, a commonly occurring natural hazard in many regions of the world, poses a major threat to population, environment and infrastructure in the areas in which they occur (Bajabaa et al. 2014; Elnazer et al. 2017). It is a largely localized event caused by exceptionally heavy rainfall (Brammer 1990; Kamal et al. 2018), and can be accompanied by other hazards such as landslides and mud flows (Collier 2007). Flash floods occur randomly in time and space and therefore forecasting these events tends to be very difficult (Kron 2005). The high velocity of flood water also substantially increases the potential for soil erosion, and flash floods can become a severe threat to lives and property within a very short period of time (Plate 2002). Land use change, such as from predominantly vegetation cover to substantially built-up, exacerbates the intensity of this type of flood by increasing the generation of runoff in the catchment area and the loss of flood attenuation capacity (Bronstert et al. 2002). The frequency and intensity of extreme precipitation events due to climate

change are expected to increase, potentially increasing the likelihood of flash flood events in the future (Adnan and Kreibich 2016; Field et al. 2012; Rahman et al. 2019).

The unique geographic and physiographic settings of Bangladesh make it prone to multiple flood types. This includes: i) river; ii) pluvial; iii) flash; iv) tidal; and v) storm-surge induced floods (Rahman and Salehin 2013). On average, 20-25% of the area is susceptible to flooding in a normal year, while extreme flood events such as those that occurred in 1987, 1988, and 1998 inundated more than 60% of the total land area (Dewan 2013; Dewan 2015). The socio-economic impacts of these recurrent floods are significant. For the period 2009 to 2014, various flood events of different magnitudes have affected, on average, 57.01% of the households in Bangladesh. The economic cost of those floods was estimated at 71.55 billion Bangladeshi Taka (0.85 billion USD) (BBS 2015). While several studies have been conducted on river and coastal floods in Bangladesh (Adnan et al. 2019; Dewan 2013), researchers so far have paid little attention to flash flooding events and impacts. Kamal et al. (2018) assessed the flash flood vulnerability of the 'Haor' community located in the north eastern region of Bangladesh. Based on available empirical data, they demonstrated that the remote location of households, lack of access to accurate weather forecasting and poor housing conditions led to significant physical damage during the flash floods. In the absence of empirical data, however, identification of the zones which are susceptible to flash flooding requires a detailed knowledge of the physical drivers triggering such floods (Choudhury et al. 2004).

The south eastern hilly region of Bangladesh is bordered by the Arakan mountains to the east and the Bay of Bengal to the west (Choudhury et al. 2004). The commercial capital of the country, Chittagong City, is located in this area and is prone to flash flooding events (Rahman and Salehin 2013). The area is known as a high-risk zone as it can experience heavy rainfall which can trigger both flash floods and landslides (Ahmed and Dewan 2017; Rahman et al. 2017). It should be noted that there can be a high spatial-temporal variation in these occurrences. Location, topography, and localized climate can all increase flooding episodes, and the additional flow through transboundary rivers has the potential to increase the flood intensity (Sarker and Rashid 2013). Predicting the occurrence of such a flood type is complex due to the fact that the water and associated materials can travel downstream very quickly to other locations where the initial rainfall event has not been observed and the flash flood event is therefore not expected (Kron 2005). An increased knowledge of causative factors could help assess the flood susceptibility of an area. For instance, steep terrain tends to generate high velocity runoff, a major contributor to a flash flood. Besides, geomorphic, drainage, and climatic conditions could also contribute to possible causes (Elnazer et al. 2017; Youssef et al. 2011). To manage flash floods effectively, morphometric factors can be used to delineate the flood-susceptible zones (Bajabaa et al. 2014; Rahman and Di 2017; Youssef et al. 2011). An examination of these factors is a major focus of this study.

Morphometric analysis of watersheds is a widely-recognized approach characterizing the hydrological response of a watershed (Bajabaa et al. 2014; Farhan et al. 2017; Rai et al. 2017; Youssef et al. 2011). Several methods are commonly used to quantify watershed geomorphology; these are primarily grouped under linear measurement and dimensionless numbers (Strahler 1957). Since morphometric parameters indicate the river basin's physical behaviour when undergoing extreme precipitation events (Diakakis 2011), several studies have combined the use of the various parameters when assessing the potential for flash floods and associated hazards (Bajabaa et al. 2014; Bhatt and Ahmed 2014; Elnazer et al. 2017; Youssef et al. 2011). In recent years, the use of a Geographic Information System (GIS) in combination with the availability of accurate spatial data, including remote-sensing data, has become an important decision-making tool in flood risk management (Abdullah et al. 2019; Elnazer et al. 2017; Lin et al. 2019). Within Bangladesh, a number of studies have been undertaken to conceptualize flash flood vulnerability in the larger catchments (Rahman and Salehin 2013; Sarker and Rashid 2013), however researchers are yet to utilise watershed morphometric analysis to estimate flood susceptibility in the smaller watersheds. This study aims to: 1) analyse the relationship of various morphometric parameters with flash flood susceptibility at the watershed level; and 2) develop a detailed, flood susceptibility map for the area.

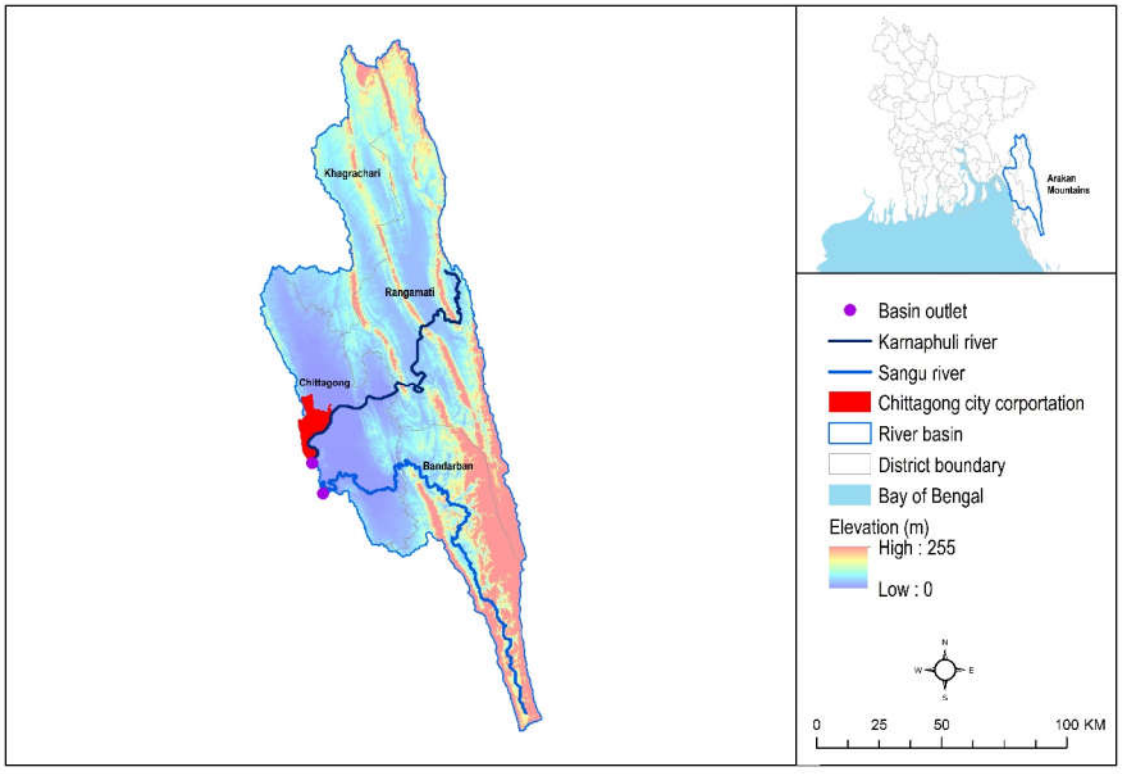

Figure 1 The Karnaphuli and Sangu river basins

2. Study area

The Karnaphuli and Sangu river basins, located in the south eastern hilly region of Bangladesh (hereinafter, region), were selected for the study (Figure 1). These basins have total areas of 8,845.18 km^2 and 3,842.82 km^2, respectively. The region is made up of 40 sub-districts within the larger Bandarban, Chittagong, Khagrachari, and Rangamati districts. The basins are mostly characterized by brown hilly soils, with 63% of the total area being composed of this type of soil. Another 13% of the area contains Non-calcareous Grey Floodplain Soils (non-saline) with 20% of the total land reserved as forest (BARC 2014).

The region is subjected to periods of heavy rainfall annually (particularly during the monsoon season) making it very prone to flash floods. The mean annual precipitation in Chittagong district, for example, is about 2,917 mm (Ahmed and Dewan 2017), signifying a high potential for flash floods events. Several of these rainfall-induced events have previously been reported to have affected either the whole or part of the two basins (Brakenridge 2018). From 1985 until 2015, heavy rainstorms badly affected the region a total of 12 times (Table 1). These events had a massive, negative impact on both population and property. For example, the torrential rain event of 23rd June 2015 triggered a flash flood that affected approximately 1.8 million people in 29 sub-districts of the Chittagong, Bandarban, and Cox's bazar districts. A post-disaster relief and rehabilitation effort was the main government response (ACAPS 2015). Biswas et al. (2012) developed an integrated watershed management (IWM) scheme for Chittagong hill tracts, and included flood control at the watershed scale as one of the major mitigation strategies. Since the impact of flash floods tends to be heterogeneous across different administrative units, the development of a susceptibility map at the watershed scale has been suggested as a measure to provide assistance to local managers in the operational planning phase. It could not only show the spatial variability of hazards on a smaller administrative scale, but could also help resource managers to control the associated risks more effectively.

Table 1 Major flash flood events reported in the south-eastern hilly region

Year	Location (districts)	Cause	Number of people affected	Source
1985	Chittagong	Heavy rain	77000	(Brakenridge 2018)
1988	Chittagong	Heavy rain	15000	(Brakenridge 2018)
1989	Chittagong, Bandarban,	Monsoonal rain	20000	(Brakenridge 2018)
1990	Chittagong, Cox's Bazar	Heavy rain	310000	(Brakenridge 2018)
1991	Chittagong, Cox's Bazar	Heavy rain	50000	(Brakenridge 2018)
1992	Chittagong	Monsoonal rain	50000	(Brakenridge 2018)

1994	Chittagong	Heavy rain	12000	(Brakenridge 2018)
1997	Chittagong, Bandarban, Rangamati, Cox's bazar	Heavy rain	239000	(Brakenridge 2018)
2000	Chittagong, Bandarban, Khagrachari, Rangamati, Cox's bazar	Monsoonal rain, torrential rain	30000	(Brakenridge 2018; Sarker and Rashid 2013)
2003	Chittagong, Khagrachari, Cox's bazar	Monsoonal rain	20000	(Brakenridge 2018; Sarker and Rashid 2013)
2012	Chittagong, Bandarban, Cox's bazar	Monsoonal rain	102000	(Brakenridge 2018; Sarker and Rashid 2013)
2015	Chittagong, Bandarban, Cox's Bazar	Torrential rain	1800000	(ACAPS 2015; Brakenridge 2018)

3. Materials and methods

3.1. Extraction of river basins

A SRTM (Shuttle Radar Topographic Mission) digital elevation model (DEM) with a spatial resolution of 30 m was obtained from EarthExplorer (https://earthexplorer.usgs.gov/). During subsequent processing to delineate watersheds, the sinks (errors) were removed and the drainage network was derived (Planchon and Darboux 2002). A flow direction raster was obtained by applying the single-direction flow algorithm (D8) (Seibert and McGlynn 2007). Two outlets of the Karnaphuli and Sangu basins were selected and boundaries generated (Figure 1).

3.2. Extraction of drainage streams and delineating watersheds

Watersheds were delineated in the two river basins using the derived drainage networks. The elevation of the extracted river basin was masked and the flow direction raster retrieved. A flow accumulation grid was generated, with each cell indicating the accumulated sums of water flowing down-slope (Kabenge et al. 2017). To create the drainage streams, a user-defined minimum threshold flow accumulation value of 100 was used (Wieczorek 2012). Subsequently a stream order was assigned by applying a stream ordering method (Strahler 1952). Strahler's ordering system assigns 1st order to streams without tributaries, 2nd order to streams with at least two 1st order tributaries, 3rd order with at least two 2nd order tributaries and so on (Hughes et al. 2011). Finally, an eight-order stream system was used to characterize the Karnaphuli and Sangu river basins (Figure 2a).

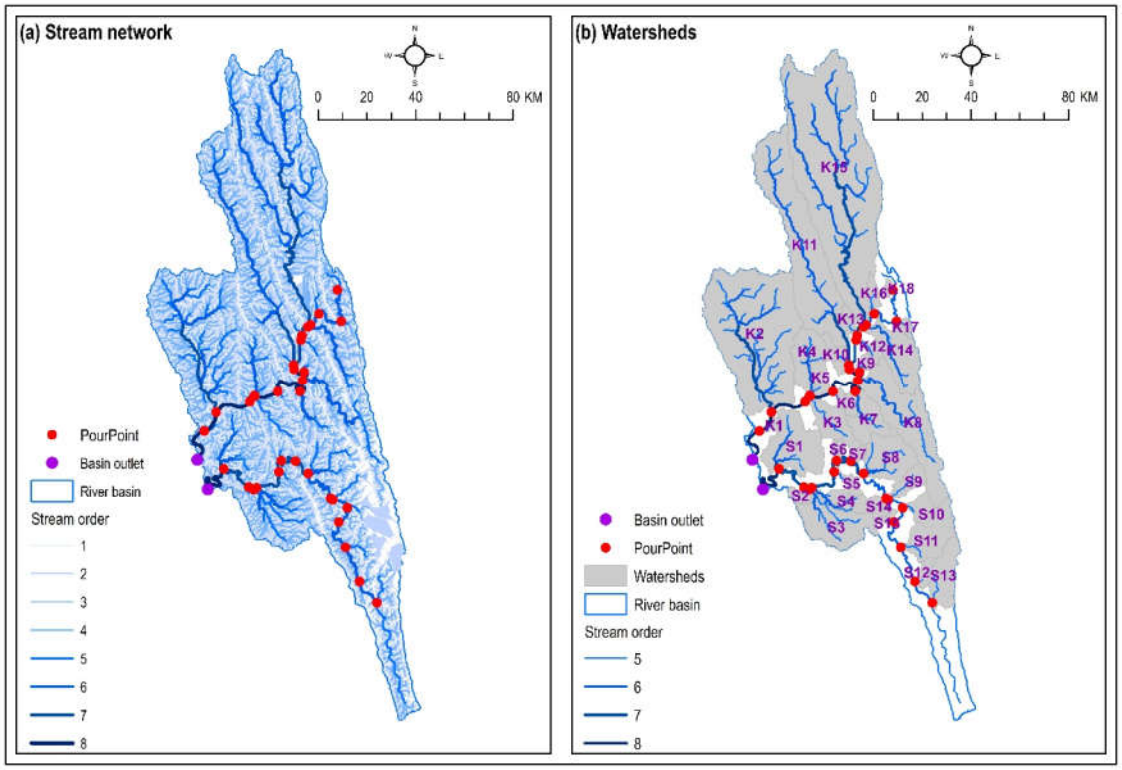

Figure 2 Stream network and watersheds of the Karnaphuli and Sangu river basin

The creation of a stream network was followed by the use of user-supplied pour points to delineate those points containing the highest water-shed flow accumulation (Rai et al. 2017). Pour points were identified on the basis that the calculated watersheds cover the whole river basins. According to Horton (1945), a well-drained basin contains 5th order stream channels; following this principle, pour points were selected in order to create watersheds of at least 5th order stream channels. Thirty-three watersheds were produced; 17 small (<100 km^2 area) and 16 large drainage basins (≥100 km^2 area) (Figure 2b).

3.3. Identifying morphometric parameters

Basin morphometric parameters provide essential information which allow the characterisation of hydro-meteorological hazards like floods (Shen et al. 2017). There is no defined, standard set of parameters that can be used for mapping flash flood susceptibility. In the literature, it is evident that different combinations of morphometric parameters have been used to determine flood hazard zones. For instance, Bajabaa et al. (2014) evaluated 26 morphometric parameters related to linear, areal, and relief characteristics. Similarly, Abdel-Fattah et al. (2017) analysed 38 parameters grouped under four classes as scale, topographic, shape and drainage network parameters. In this study, 29 morphometric parameters were selected under the four broad classes proposed by Abdel-Fattah et al. (2017) that provided a comprehensive picture of each drainage basin. The values of selected parameters were

obtained using the corresponding equations, calculated using a GIS. Table 2 shows selected morphometric parameters along with the associated equations.

Four 'scale' parameters were selected: i) basin area, ii) perimeter, iii) basin length, and iv) time of concentration. Basin area is a common parameter used to estimate stream discharge. This normally demonstrates a strong positive correlation with peak discharge as a bigger basin will receive a higher amount of precipitation, and therefore will generate a larger pulse of runoff (Abdel-Fattah et al. 2017). Time of concentration indicates the time that water is needed to reach the outlet (Bhatt and Ahmed 2014). An inverse correlation exists between the time of concentration and runoff generation. A longer time of concentration of a basin means a higher probability of ground water recharge, hence less runoff (Bajabaa et al. 2014).

Various topographic parameters, including slope, elevation, relief and ruggedness number can influence flash flood occurrence. For instance, a steep slope increases the speed of runoff, therefore increasing the probability of inundation of areas with relatively gentle slope and elevation (Kabenge et al. 2017). On the other hand, a low surface slope reduces runoff velocity, providing a greater degree of surface infiltration and water recharge, and lowering peak flow (Bajabaa et al. 2014). A ruggedness number is the product of drainage density and relief divided by 1000. A ruggedness <1 means smooth topography, a value of 1-2 indicates sharper topography, and extreme values (>2) indicate 'badland' (areas where the bedrock is poorly cemented) topography. Watersheds with a high ruggedness number therefore receive a higher discharge, leading to a greater probability of flash flooding occurring (Farhan et al. 2017).

The values of different shape parameters can also explain the volume and intensity of runoff in watersheds. One such parameter is the form factor which characterises the runoff intensity in a basin. The higher the form factor value, the less the elongation of a basin, meaning that flow peaks over a shorter time period. The form factor value of a perfectly circular basin should be less than 0.79 (Farhan et al. 2017). The elongation ratio is "the ratio between the diameter of a circle with the same area as the basin and the maximum length of the basin as measured for the relief ratio" (Schumm 1956). It maintains an inverse relationship with flash flood as, for a given rainfall event, the basin with the smaller elongation ratio will generate a higher peak discharge. The elongation ratio can vary from 0.6-1.0, with a value close to 1.0 indicating low basin relief (Stralher 1964). Another shape parameter is the circularity ratio, which denotes the ratio of a circumference of a circle having the same area as the catchment to its perimeter (Schumm 1956). This ratio carries a positive correlation with runoff generation as watersheds with a higher circularity ratio are characterized by high relief, are less elongated, and less permeable, and hence have a higher probability of generating a greater quantity of runoff (Farhan et al. 2017).

The runoff generation potential of a basin also varies with the different properties of stream systems. For instance, stream numbers are positively correlated with volume of runoff (Youssef et al. 2011). The total stream length of different watersheds is a major hydrological property that positively influences generation of runoff (Farhan et al. 2017). Longer stream length is responsible for a higher volume of runoff, leading to a flash flood occurrence (Bajabaa et al. 2014; Youssef et al. 2011). Stream frequency is defined as the number of streams per unit of basin area and drainage density is the ratio of total streams length to a basin area (Horton 1945). These two parameters are positively correlated with generation of runoff (Farhan et al. 2017). Generally, watersheds with low drainage density create suitable conditions for infiltration. Conversely, high stream frequency refers to areas of impermeable sub-surface material and reduced infiltration capacity (Youssef et al. 2011). The usefulness of drainage density and stream frequency, however, is limited when used to compare the drainage morphometric characteristics between large and small basins. For instance, the number of streams per unit of basin area could be the same for both a large and a small basin (Horton 1945). This limitation can be overcome by estimating the texture ratio, a metric denoting the ratio of stream number to basin perimeter (Smith 1950). Lower values of texture ratio are associated with lower degrees of slope which create a more favourable environment for infiltration, and thus, low runoff (Bajabaa et al. 2014). The weighted mean bifurcation ratio is the final parameter that characterises stream systems in various watersheds. The bifurcation ratio is defined as "the average number of branching or bifurcations of streams of a given order to that of streams of the next lower order*"* (Horton 1945), which has an inverse relationship with runoff generation (Bajabaa et al. 2014).

Table 2 Morphometric parameters and corresponding equations

Parameters	**Symbol**	**Equation / explanation**	**Equation Source**
Scale parameters			
Basin area (km^2)	A	Area of each watershed	
Perimeter (km)	P	Perimeter of each watershed	
Basin length (km)	L_b	Maximum length of each watershed	
Time of concentration	T_c	$T_c = 0.542(L_{ms}/S_{ms})^2$	(Abdel-Fattah et al. 2017)
Topographic parameter			
Mean elevation (m)	H_m	Mean elevation of each watershed	
Maximum elevation (m)	H_{max}	Maximum elevation of each watershed	
Basin mouth elevation (m)	H_{min}	Elevation at pour points	

Total Basin Relief (m)	R	$R = (H_{max} - H_{min})$	(Schumm 1956)
Relief ratio	R_{hl}	$R_{hl} = R/L_b$	(Schumm 1956)
Ruggedness number	R_n	$R_n = D_d \times (R/1000)$	(Melton 1957)
Mean basin slope	S_b	Average slope of each watershed	
Mainstream slope	S_{ms}	Average mainstream slope of each watershed	
Slope ratio	S_r	$S_r = S_{ms}/S_b$	(Horton 1945)
Longest stream slope	S_{ls}	Average slope of longest stream in each watershed	
Shape parameters			
Form factor	F	$F = A/L_b^2$	(Horton 1932)
Compactness ratio	C	$C = P/2\sqrt{\pi A}$	(Horton 1932)
Circularity ratio	R_c	$R_c = 4\pi A/P^2$	(Schumm 1956)
Elongation ratio	R_e	$2\sqrt{A/\pi}/L_b$	(Schumm 1956)
Drainage network parameters			
Stream order	U	Number of stream orders in each watershed	(Strahler 1952)
Stream number	N_u	Total stream number in each watershed	
Stream length (km)	L_u	Total stream length in each watershed	
Mainstream length (km)	L_{ms}	Mainstream length in each watershed	
Longest stream length (km)	L_{ls}	Longest stream length in each watershed	
Stream frequency	F_s	$F_s = N_u/A$	(Horton 1945)
1st order stream frequency	F_1	F_1 = 1st order stream number / A	(Abdel-Fattah et al. 2017)
Drainage density	D_d	$D_d = L_u/A$	(Horton 1945)
Drainage texture	T	$T = D_d/F_s$	(Smith 1950)
Texture ratio	R_t	$R_t = N_u/P$	(Smith 1950)
Bifurcation ratio	R_b	$R_{bu} = N_u/N_{u+1}$	(Horton 1945)
Weighted mean bifurcation ratio	B_w	$B_w = \frac{1}{\sum_1^{max(U)-1}(N_u + N_{u+1})} \sum_1^{max(U)-1} R_{bu}(N_u + N_{u+1})$	(Shen et al. 2017)

3.4. Mapping flash flood susceptible zones

3.4.1. Analysing relationships of morphometric parameters with flood susceptibility

A rank (y) was assigned to each watershed according to the level of flood susceptibility using a relative ranking method in which 1 denotes a very low, and 5 a very high susceptibility in relation to the value of each morphometric parameter (x). Ranks were estimated by applying a linear interpolation technique proposed by Davis (2002). If the value of a morphometric parameter is positively correlated with the occurrence of a flash flood event, then equation 1 was used. Otherwise equation 2 was applied.

$$If\ y\ \propto x, \qquad y_n' = \frac{(y_2 - y_1)(x_n' - x_{\min}\ )}{(x_{max} - x_{\min}\ )} + y_1 \tag{1}$$

$$If\ y\ \propto \frac{1}{x}, \qquad y_n' = \frac{(y_2 - y_1)(x_n' - x_{\max}\ )}{(x_{min} - x_{\max}\ )} + y_1 \tag{2}$$

y_n' is the susceptibility rank of a parameter for the nth watershed (n = 1, 2, 3, …., 33); the maximum rank y_2 = 5; minimum rank y_1 = 1; x_n' is the value of a parameter for the nth watershed; x_{max} is the maximum value of a parameter among all watersheds, and x_{min} is the minimum value of a parameter among all watersheds.

As simulated hydrographs for the various watersheds within the region were not available, various studies depicting the pattern of relationships between flash floods and morphometric parameters were obtained and assessed. From these studies, the relationship of 22 (out of 29) morphometric parameters were determined (Table 3).

Table 3 Relationship of various morphometric parameters with peak runoff

Parameters	**Relation with peak runoff**	**Reference**
Basin area (A)	Positive correlation	(Abdel-Fattah et al. 2017; Youssef et al. 2011)
Basin length (L_b)	Positive correlation	(Abdel-Fattah et al. 2017; Bajabaa et al. 2014)
Time of concentration (T_c)	Negative correlation	(Youssef et al. 2011)
Mean elevation (H_m)	Positive correlation	(Abdel-Fattah et al. 2017; Bajabaa et al. 2014)
Total Basin Relief (R)	Positive correlation	(Abdel-Fattah et al. 2017; Bajabaa et al. 2014; Youssef et al. 2011)
Relief ratio (R_{hl})	Positive correlation	(Abdel-Fattah et al. 2017; Youssef et al. 2011)

Ruggedness number (R_n)	Positive correlation	(Farhan et al. 2017)
Mean basin slope (S_b)	Positive correlation	(Abdel-Fattah et al. 2017; Bajabaa et al. 2014; Schmidt et al. 2000)
Mainstream slope (S_{ms})	Positive correlation	(Abdel-Fattah et al. 2017)
Slope ratio (S_r)	Negative correlation	(Abdel-Fattah et al. 2017)
Longest stream slope (S_{ls})	Positive correlation	(Schmidt et al. 2000)
Form factor (F)	Positive correlation	(Abdelkareem 2017; Farhan et al. 2017; Youssef et al. 2011)
Compactness ratio (C)	Negative correlation	(Youssef et al. 2011)
Circularity ratio (R_c)	Positive correlation	(Abdel-Fattah et al. 2017; Farhan et al. 2017; Youssef et al. 2011)
Elongation ratio (R_e)	Negative correlation	(Bajabaa et al. 2014; Youssef et al. 2011)
Total stream number (N_u)	Positive correlation	(Abdel-Fattah et al. 2017; Youssef et al. 2011)
Total stream length (L_u)	Positive correlation	(Youssef et al. 2011)
Mainstream length (L_{ms})	Positive correlation	(Abdel-Fattah et al. 2017)
Stream frequency (F_s)	Positive correlation	(Youssef et al. 2011)
Drainage density (D_d)	Positive correlation	(Youssef et al. 2011)
Texture ratio (R_t)	Positive correlation	(Abdel-Fattah et al. 2017; Bajabaa et al. 2014)
Weighted mean bifurcation ratio (B_w)	Negative correlation	(Bajabaa et al. 2014)

3.4.2. Flood susceptibility mapping

Twenty-two flood susceptibility maps (constructed using the individual morphometric parameters) were used to estimate the total rank of each of the 33 watersheds. Here, the total rank of each watershed was estimated by adding all scores (rank) obtained for 22 morphometric parameters. The aggregated map was categorised (using the equation 1 formula) into five susceptibility classes - 'very low', 'low', 'moderate', 'high', and 'very high'. In order to allow the resulting watershed-wise flood susceptibility maps to be easily interpreted by policy makers, the maps were disaggregated at the sub-district level, and the different sub-districts categorised according to the degree of flash flood potential. Since the river basins contained segments from 40 different sub-districts, the level of flood susceptibility at different sub-districts was noted as a percentage of the total area within the basin. The number of people

exposed to each category of flood susceptible zone was also calculated. This process was conducted for each sub-district. Gridded population data at 100 m resolution was obtained from Worldpop (WorldPop 2017) in order to estimate flood-exposed population numbers

4. Results and discussion

4.1. Relationships of morphometric parameters with flood susceptibility

4.1.1. Scale parameter

The flash flood susceptibility ranking of different watersheds in relation to the three scale parameters noted previously is shown in Figure 3. The study delineated watersheds with areas ranging from 22 km^2 to 2,699 km^2, the range in size indicating the heterogeneous nature of the drainage basins. The larger area and greater length of the three watersheds in the Karnaphuli river basin (K2, K11, and K15) resulted in a flood susceptibility ranking of greater than 3. It should be noted, however, that a watershed with a larger area provides a greater degree of attenuation, reducing the susceptibility to flash flood events. For example, watershed K15 has the highest time of concentration i.e., 1562.69 min. Generally, the Karnaphuli river basin has relatively a greater time of concentration than the Sangu river basin (Table 4).

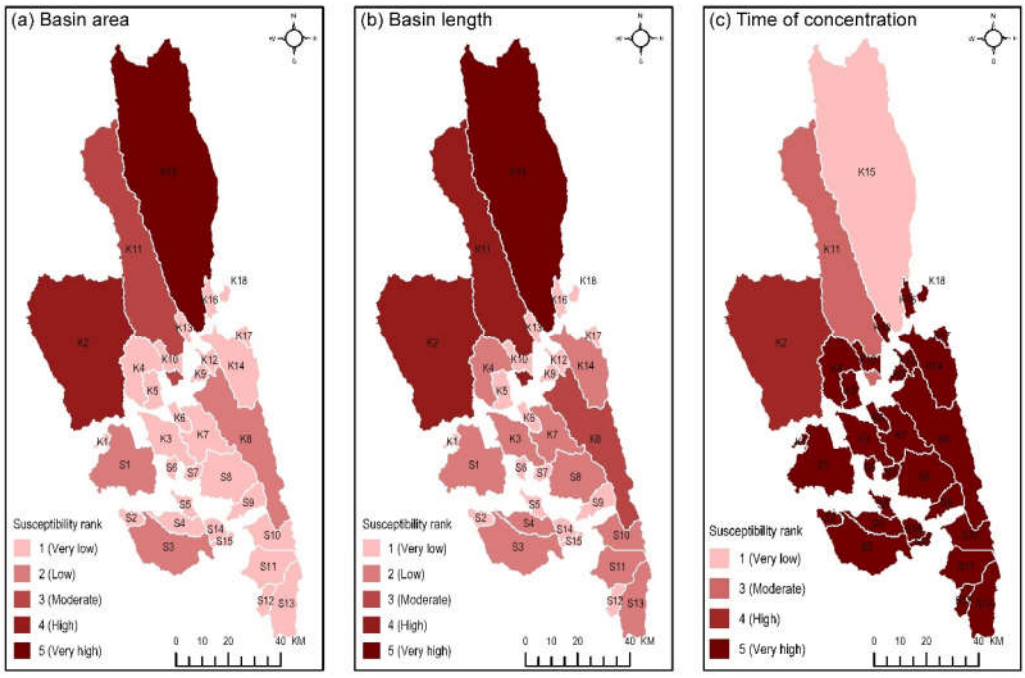

Figure 3 Flash flood susceptibility ranking in relation to scale parameters

255 Table 4 Morphometric characteristics of the Karnaphuli and Sangu river basins in south-eastern Bangladesh

Watershed number	Morphometric parameters																				
	A	L_b	T_c	H_m	R	R_{hl}	R_n	S_b	S_{ms}	S_r	S_{ls}	F	C	R_c	R_e	N_u	L_u	L_{ms}	F_s	D_d	R_t	B_w
K1	21.6	7.5	47.98	6.3	21	2.79	0.06	1.75	0.63	0.36	1.94	0.49	3.41	0.09	0.70	71	59.2	5.9	3.28	2.74	1.26	4.96
K2	1733.1	90.7	435.21	41.4	254	2.80	0.70	4.90	1.67	0.341	1.67	0.27	2.24	0.20	0.52	5752	4786.2	47.3	3.32	2.76	17.41	5.58
K3	221.4	28.2	132.50	49.1	152	5.39	0.42	5.90	1.99	0.338	1.99	0.35	2.40	0.17	0.60	760	605.1	31.1	3.43	2.73	6.01	5.43
K4	260.0	30.9	81.50	61.1	249	8.06	0.67	8.29	2.00	0.241	2.00	0.35	2.41	0.17	0.59	842	701.4	24.5	3.24	2.70	6.11	5.35
K5	92.0	17.1	8.14	21.0	121	7.07	0.51	3.73	1.82	0.488	1.61	0.40	2.20	0.21	0.63	352	386.8	7.0	3.83	4.21	4.71	5.99
K6	54.2	12.7	0.69	72.3	244	19.26	0.63	10.58	3.19	0.301	7.04	0.43	2.13	0.22	0.66	189	140.2	3.6	3.49	2.59	3.40	4.65
K7	249.5	30.2	3.39	107.8	239	7.92	0.61	10.81	7.73	0.715	7.73	0.35	2.53	0.16	0.59	791	641.6	19.3	3.17	2.57	5.58	5.69
K8	723.9	55.2	25.67	174.4	224	4.06	0.52	8.57	7.23	0.844	7.23	0.30	2.60	0.15	0.55	2089	1685.3	49.8	2.89	2.33	8.42	5.23
K9	36.9	10.2	1.64	58.5	98	9.62	0.26	6.85	3.05	0.446	3.05	0.45	2.02	0.24	0.67	114	96.1	5.3	3.09	2.61	2.62	4.84
K10	67.2	14.3	9.20	83.0	224	15.64	1.20	8.63	1.51	0.175	5.31	0.42	2.32	0.19	0.65	245	358.6	6.2	3.65	5.34	3.63	7.73
K11	1310.7	77.4	672.23	87.2	224	2.89	0.64	7.64	0.74	0.096	2.39	0.28	3.18	0.10	0.53	4211	3717.8	25.9	3.21	2.84	10.30	5.53
K12	48.7	11.9	4.72	117.5	224	18.79	0.55	12.15	3.58	0.295	3.58	0.43	2.40	0.17	0.66	159	120.3	10.6	3.27	2.47	2.68	5.09
K13	44.5	11.3	1.20	116.6	224	19.78	0.55	10.52	4.14	0.393	8.76	0.44	2.12	0.22	0.66	130	109.1	6.2	2.92	2.46	2.60	6.55
K14	349.5	36.5	29.19	127.6	224	6.13	0.58	9.69	4.71	0.486	4.71	0.33	2.20	0.21	0.58	1069	908.8	34.5	3.06	2.60	7.32	5.50
K15	2698.5	116.6	1562.69	113.8	224	1.92	0.71	8.39	1.84	0.219	1.84	0.25	2.33	0.18	0.50	8966	8546.4	98.6	3.32	3.17	20.91	5.52
K16	53.9	12.6	2.60	134.8	224	17.74	0.57	12.45	5.10	0.41	5.10	0.43	2.19	0.21	0.66	162	136.1	11.2	3.01	2.53	2.84	6.37
K17	33.7	9.7	0.23	149.4	218	22.54	0.54	11.95	6.01	0.503	8.42	0.46	1.89	0.28	0.68	122	83.8	3.9	3.62	2.49	3.14	5.93
K18	23.3	7.8	0.19	64.8	162	20.65	0.47	7.83	1.51	0.192	4.35	0.48	2.11	0.23	0.69	79	68.1	0.9	3.39	2.92	2.19	5.00
S1	465.5	43.0	2.26	16.7	134	3.12	0.38	3.32	1.73	0.521	1.67	0.32	2.43	0.17	0.57	1645	1317.6	3.5	3.53	2.83	8.86	5.34
S2	52.6	12.5	1.06	24.2	86	6.90	0.23	4.43	1.83	0.413	2.20	0.43	2.31	0.19	0.66	168	142.7	2.6	3.20	2.71	2.83	5.68
S3	424.0	40.8	25.46	53.4	250	6.13	0.67	5.30	1.98	0.374	3.07	0.32	2.44	0.17	0.57	1371	1134.8	13.6	3.23	2.68	7.69	5.88
S4	134.0	21.2	43.29	66.5	249	11.75	0.65	6.55	1.94	0.296	3.44	0.38	2.56	0.15	0.62	428	352.1	17.4	3.19	2.63	4.08	5.87
S5	52.5	12.4	2.61	96.9	245	19.69	0.63	10.39	2.93	0.282	4.66	0.43	2.45	0.17	0.66	163	135.9	6.4	3.11	2.59	2.59	5.47
S6	34.7	9.8	0.71	51.1	106	10.78	0.29	8.96	4.41	0.492	4.41	0.46	1.94	0.27	0.68	113	94.5	5.0	3.26	2.72	2.79	5.52
S7	36.9	10.2	0.27	64.1	139	13.64	0.37	10.26	4.44	0.433	6.52	0.45	1.81	0.31	0.67	112	98.9	3.1	3.03	2.68	2.88	5.51
S8	326.4	35.1	1.28	140.1	242	6.89	0.62	9.67	7.81	0.808	10.74	0.34	1.87	0.29	0.58	1014	834.6	12.0	3.11	2.56	8.49	5.37
S9	107.7	18.7	1.13	204.9	246	13.14	0.55	6.99	12.31	1.761	12.31	0.39	2.06	0.23	0.63	286	238.9	17.8	2.66	2.22	3.77	5.55

S10	182.0	25.2	0.31	245.4	226	8.96	3.29	2.06	9.74	4.722	0.00	0.36	2.09	0.23	0.60	681	2649.9	7.4	3.74	14.56	6.80	38.53
S11	215.3	27.7	0.81	225.5	213	7.68	2.02	5.39	10.91	2.024	0.00	0.36	1.73	0.33	0.60	848	2038.2	13.3	3.94	9.47	9.43	11.64
S12	56.9	13.0	0.04	210.4	214	16.43	0.47	8.25	14.17	1.717	10.74	0.43	2.03	0.24	0.65	174	124.8	3.7	3.06	2.19	3.21	4.85
S13	244.8	29.8	0.47	234.8	193	6.47	1.64	4.38	15.44	3.528	0.00	0.35	1.89	0.28	0.59	834	2077.2	14.4	3.41	8.49	7.94	9.90
S14	59.6	13.4	0.02	162.6	218	16.30	0.52	12.20	9.67	0.792	11.81	0.42	1.84	0.30	0.65	183	143.4	1.7	3.07	2.41	3.64	5.48
S15	29.3	8.9	0.01	164.6	236	26.41	0.59	11.41	13.41	1.176	12.41	0.47	2.18	0.21	0.68	85	72.6	1.5	2.90	2.48	2.03	4.99

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4.1.2. Topographic characteristics

A difference in elevation was also noted between the two river basins. The mean elevation of the watersheds ranged in height from 6m to 255m. The eastern parts of the study area have a generally higher elevation than those in the central and southwestern parts (Figure 1). Three watersheds (S10, S11, S13) in the southern part of the study area received the highest flood susceptibility rank (Figure 4a). Basin relief, which represents the difference in elevation between the highest point and the basin outlet, can determine the runoff potential of a watershed. A greater basin relief is less conducive to rapid surface water infiltration, with the volume of the resulting overland flow/surface water (theoretically) making an area more susceptible to flooding. A similar relationship exists between the relief ratio and a flash flood event. While a higher susceptibility rank was estimated for most of the watersheds in terms of basin relief, only a few of the smaller watersheds were deemed susceptible to flash flooding due to their high relief ratio (Figure 4 (b-c)).

Of the watersheds examined, 29 have a ruggedness number of <1. Two watersheds indicate a ruggedness number from 1 to 2 and the remaining two watersheds have an extreme ruggedness number, i.e. >2 (Table 4). The susceptibility rank of ≥ 3 was estimated for three watersheds (S10, S11, and S13) (Figure 4d). Surfaces with a relatively high slope value characterize most of the region. The degree of basin and mainstream slope, the longest stream, and basin size positively influences generation of runoff. Figure 4 (e-h), shows flood-susceptible areas related to mean basin slope, mainstream slope, and the longest stream slope. In relation to slope ratio, 23 watersheds received the highest flood susceptibility rank due to a high slope ratio (Figure 4g).

Figure 4 Flash flood hazard ranking in relation to topographic parameters

4.1.3. Shape parameter

The estimated form factor values for all watersheds in the two basins were less than 0.79 (Table 4), indicating that the shape of the individual basins is essentially circular. Based on this observation, 13 watersheds were given the highest susceptibility rank of 5 (Figure 5a). As the compactness ratio is inversely related to flash flooding, the ratio was used to calculate a flash flood susceptibility rank of ≥3 for the 21 watersheds (Figure 5b). In relation to circularity ratio, 14 watersheds were found to be in

moderate to very high flood susceptible zones (Figure 5c). In regards the elongation ratio value, the flood potential in five watersheds is high (susceptibility rank ≥ 4) (Figure 5d).

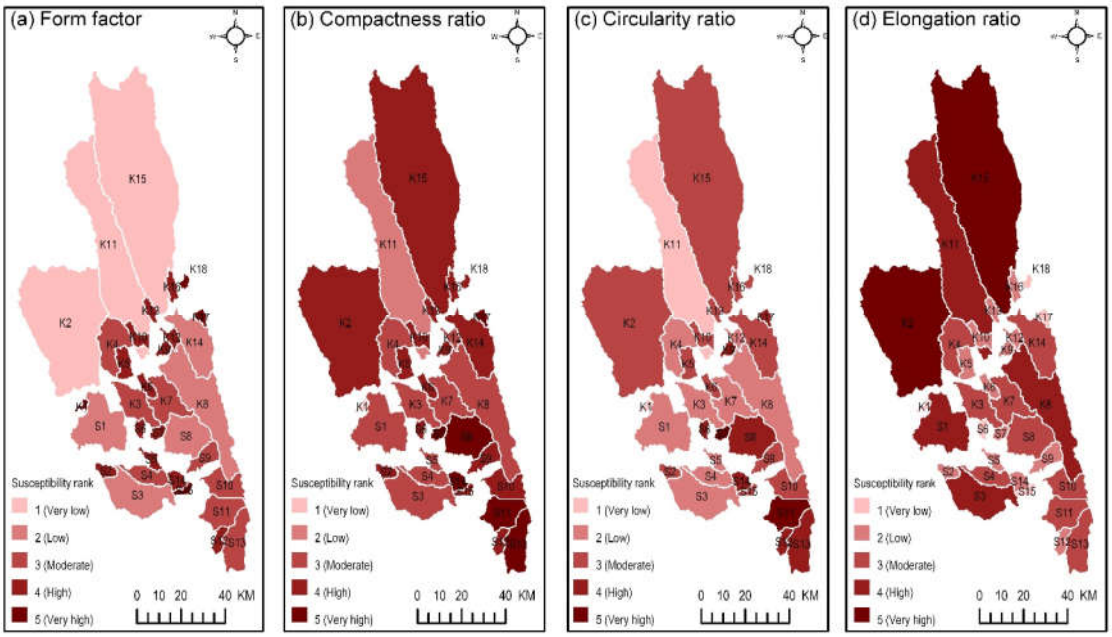

Figure 5 Flash flood hazard ranking in relation to shape parameters

4.1.4. Characteristics of the stream systems

Depending on the size of a watershed, stream number in the two river basins ranged from 71 (K1) to 8966 (K15). Likewise, total stream lengths and mainstream lengths vary from 59.2km to 8,546.4km and 0.88km to 98.57km, respectively (Table 4). In relation to stream number and total stream lengths, the three largest watersheds (K2, K11 and K15) indicate a high degree of flood susceptibility (Figure 6(a-b)). Along with the watersheds K2 and K15, the higher mainstream length of K8 also makes it more susceptible to floods (Figure 6c).

Other characteristics of the stream systems used in the study include stream frequency, drainage density, texture ratio, and weighted mean bifurcation ratio. These parameters help explain the pattern of runoff generation that contributes to flash floods in the region as they are positively correlated with flash flood occurrence. In the watersheds of the two basins, the range of stream frequency and drainage density is found to be 2.66-3.94 and 2.19-14.56, respectively. With respect to stream frequency, 17 watersheds are susceptible to floods, as indicated by a rank of ≥ 3 (Figure 6d). Drainage density influences the occurrence of flash flood in three of the smaller watersheds (S10, S11, and S13) (Figure 6e). With regard to the texture ratio, four of the larger watersheds also appear prone to floods (Figure 6f). Most of the watersheds in the region have a weighted mean bifurcation ratio of 4-6, again indicating a high

degree of flood susceptibility. Watershed S10 received the lowest rank due to its high mean bifurcation ratio (Figure 6 g).

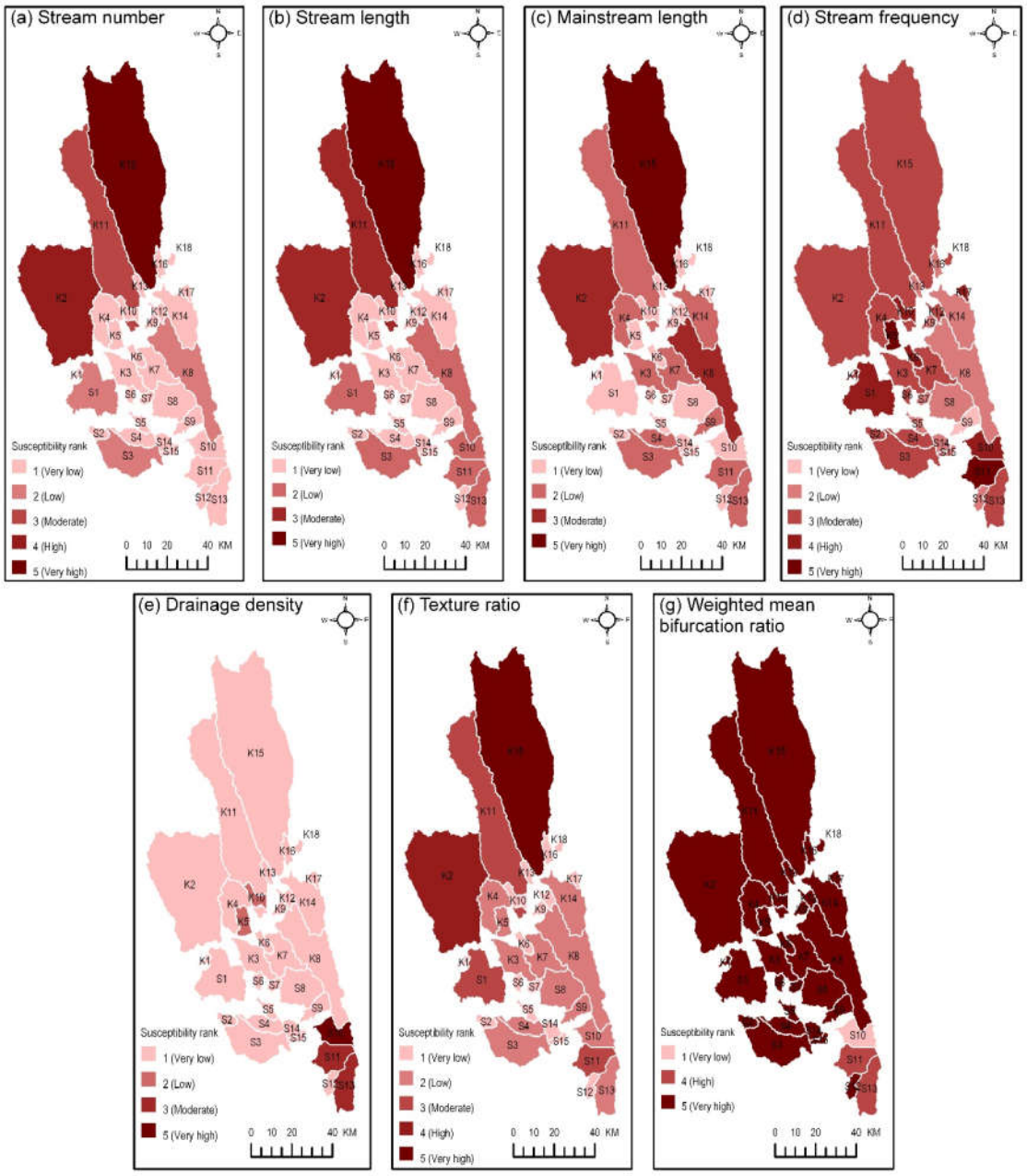

Figure 6 Flash flood hazard ranking in relation to the stream characteristics

4.2. Flash flood susceptibility zones

A flash flood susceptibility map of the two river basins is shown in Figure 7. This indicates that several watersheds are highly susceptible to flash flood. For example, watershed K15 is located in a 'very high' flood susceptibility category. A total of 10 watersheds have been categorised as 'high', while 17

watersheds are located in ‘moderate’ susceptibility zones. These results also indicate that only five watersheds have low flooding potential (as indicated by a susceptibility level of ‘low’ to ‘very low’) . The larger watersheds (those with a basin area greater than 100km^2 (Bajabaa et al. 2014)) also tend to receive a greater amount of precipitation. The larger watersheds also tend to have greater attenuation capacity, however the higher elevations associated with these areas, as well as greater slope angles and more varied relief, may lead to lower surface infiltration, greater overland flow and therefore an associated higher peak runoff. Due to these factors, most of the larger size watersheds were categorised as having ‘moderate’ to ‘very high’ susceptibility to flash floods.

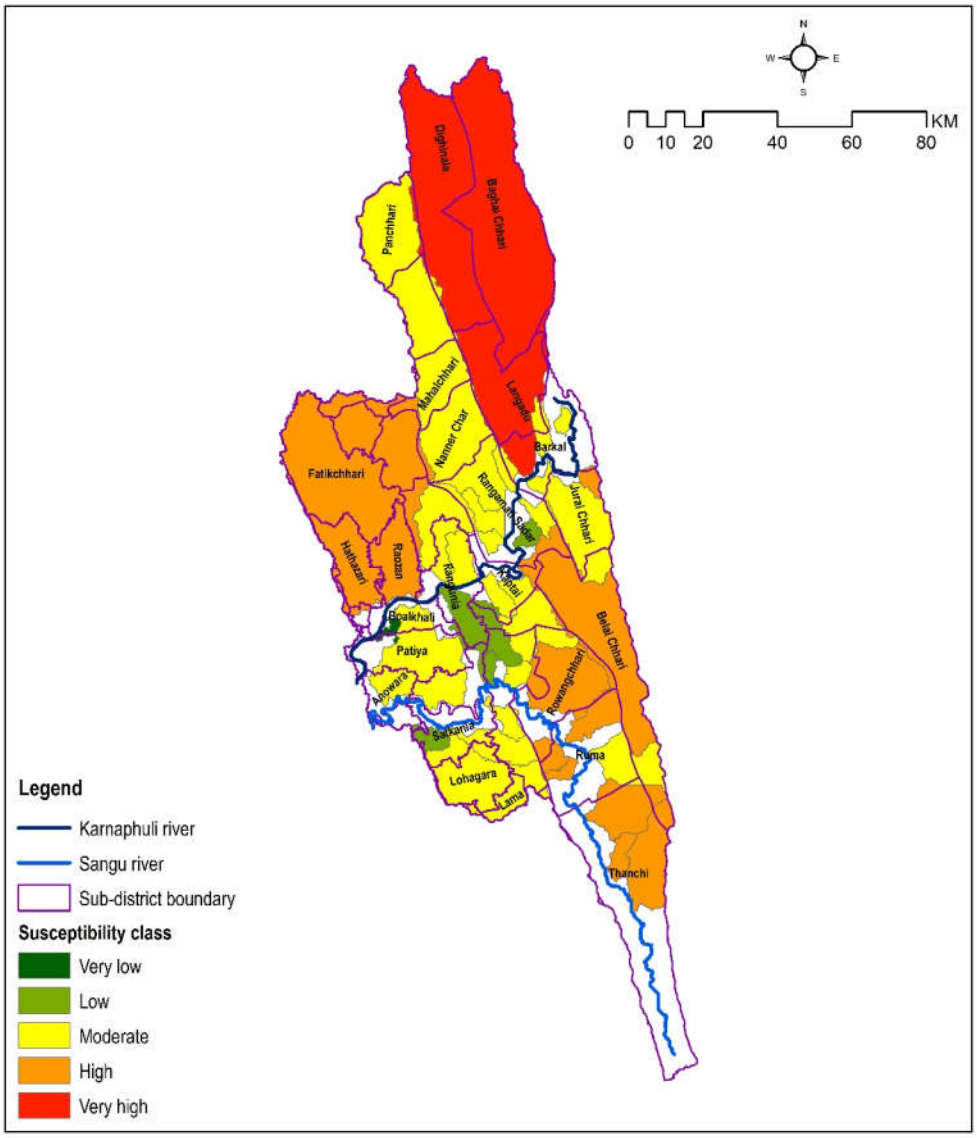

Figure 7 Flash flood hazard map of the Karnaphuli and Sangu river basins

The watershed-based hazard assessment highlighted the flood susceptible zones. To enable the map to be used effectively for local hazard management, localities at the sub-district level were defined and

mapped and the number and location of people exposed to flash flood events was determined. The percentage of area within each identified flood-susceptible zone was calculated for each sub-district (Table 5). Most of the these were categorized as 'moderate' or 'high' flood susceptible zones and had been affected by floods during different historical events. For instance, the whole area in Raozan sub-district is susceptible to a flood of 'high' severity. About 45,000 people in Raozan sub-district were affected during the 2015 event (ACAPS 2015). More than two-thirds of the area within 11 sub-districts of Chittagong district were identified as being susceptible to flash flood. This indicates a significant threat to the country's trade and commerce, as this area is the commercial capital of Bangladesh. It should also be noted that, although the geomorphological characteristics of the area play a large part in the susceptibility to flash flooding events, anthropogenic activities such as hill cutting are also believed to have played a part in amplifying the recent impacts of floods (Sarker and Rashid 2013).

Table 5 Areas susceptible to flash floods in the two river basins

District	**Sub-district**	**Percentage (%) of hazard area**				
		Very low	**Low**	**Moderate**	**High**	**Very high**
Bandarban	Bandarban Sadar	0	22	68	10	0
	Lama	0	0	100	0	0
	Rowangchhari	0	0	14	86	0
	Ruma	0	0	35	65	0
	Thanchi	0	0	1	99	0
Chittagong	Anowara	0	0	100	0	0
	Banshkhali	0	68	32	0	0
	Boalkhali	19	6	75	0	0
	Chandanaish	0	14	86	0	0
	Chandgaon	42	0	0	58	0
	Fatikchhari	0	0	0	100	0
	Hathazari	0	0	0	100	0
	Lohagara	0	0	100	0	0
	Mirsharai	0	0	0	100	0
	Pahartali	0	0	0	100	0
	Panchlaish	0	0	0	100	0
	Patiya	3	2	95	0	0
	Rangunia	0	37	62	1	0
	Raozan	0	0	0	100	0
	Satkania	0	32	68	0	0
	Sitakunda	0	0	0	100	0
Khagrachari	Dighinala	0	0	1	0	99
	Khagrachhari Sadar	0	0	98	0	2
	Lakshmichhari	0	0	0	100	0
	Mahalchhari	0	0	88	12	1
	Manikchhari	0	0	0	100	0
	Matiranga	0	0	100	0	0
	Panchhari	0	0	95	0	5

	Ramgarh	0	0	3	97	0
Rangamati	Baghai Chhari	0	0	0	0	100
	Barkal	0	0	49	1	49
	Belai Chhari	0	0	16	84	0
	Jurai Chhari	0	0	88	12	0
	Kaptai	0	9	75	16	0
	Kawkhali (Betbunia)	0	0	71	29	0
	Langadu	0	0	6	0	94
	Nanner Char	0	0	94	5	1
	Rajasthali	0	22	72	5	0
	Rangamati Sadar	0	8	79	12	0

The number of people exposed to different flash flood zones in the different sub-districts is shown in Figure 8. The term population exposure means the total number of people located within the 'moderate' to 'very high' level susceptibility zones. The analysis showed that about 0.48 million people in Fatikchhari sub-district live in the "very high" flood susceptible zone. The 2015 event affected approximately 17,000 people in this sub-district and damaged 200 houses (ACAPS 2015). Likewise, about 0.36 million people in Raozan sub-district live in 'high' level flood susceptible areas. Despite the flood susceptibility level of the K15 watershed being very high, the number of people actually exposed to flooding is low since relatively few people live in this area. Other sub-districts located in K15 (with associated figures for population exposure) are Dighinala (85,000), Baghai Chhari (64,000) and Langadu (78,000).

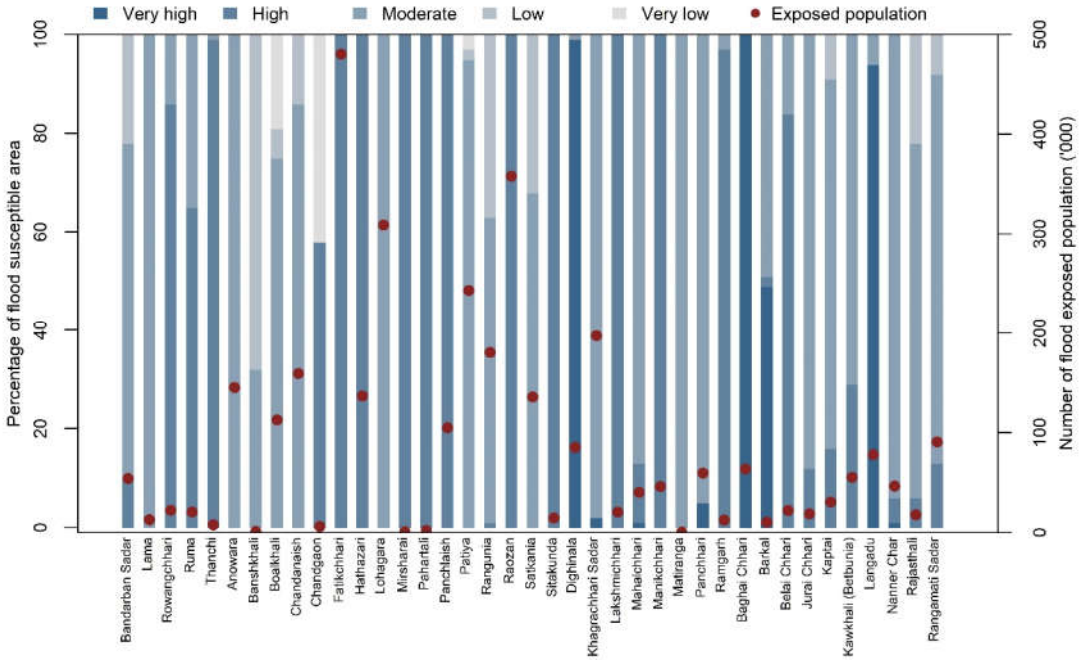

Figure 8 Number of people exposed to flash flood in different sub-districts

5. Conclusion

This GIS-based study defined morphometric parameters accountable for flash flood hazard in watersheds of the Karnaphuli and Sangu river basins. A digital elevation model was obtained and used to derive drainage networks and river basins. The study estimated 22 morphometric parameters and grouped them into four categories in order to examine the parameter relationships with peak runoff flows which contribute to flash flooding. These were then used to create a map of flash flood susceptibility based on the sub-district boundaries. Overlying the sub-district map on gridded population data assisted in identifying the population exposure numbers within the various zones.

The study results indicated that flash flood hazards are mainly associated with the volume of water runoff, the associated water velocity and the amount of infiltration occurring during the surface water flow. The large watersheds receive a higher amount of precipitation, resulting in a greater volume of runoff. Elevation, slope angle and basin relief characteristics also influence the flood susceptibility of these basins. The study also indicated that hilly areas within the study region are at risk of severe inundation and so it is fortunate that relatively few people live in these areas. A substantial number of people, however, do live in the 'high' flood susceptible zones in the various sub-districts and are therefore exposed to the associated increased risks to lives, livelihood and property by flood events.

Flash flood susceptibility mapping, through the use of morphometric analysis, overcomes the limitation of hydrological flood models which are time-consuming to construct, and which are difficult to apply over larger areas (Youssef et al. 2011). This study does, however, have some limitations. Relative flood risk and the ranking of flood susceptibility in various watersheds were determined, with a focus on assessing flood susceptibility at the watershed scale. The inability to obtain actual flood data, however, makes it difficult to map flood susceptibility at a microscale. Although remote sensing data (such as Landsat images) provides information which can be useful for observing flood inundation (Rahman and Di 2017), the presence of cloud cover during the monsoon season (Adnan et al. 2019) makes it very difficult to accurately observe flash flood events with satellite data. An additional factor is the speed of rise and subsidence of water during a flash flood event, as opposed to the longer time taken by riverwater flooding events.

Despite the limitations noted above, the study does provide an overview of the flash flood hazard zones identified in a region of national importance, and the associated level of exposure of the population to these hazards. A focus on flash flood susceptibility mapping at the sub-district level also enables the deployment of flood risk mitigation strategies by the local organizations responsible for watershed management. A knowledge of the flood susceptibility level of each watershed/sub-district can be of great benefit in the development of any such strategies. The study also provides some direction for future research. Synthetic-aperture radar (SAR) images, which have the ability to penetrate cloud, can be employed to observe flash floods and map microscale flood susceptibility (Rahman and Di 2017).

Hydrologically dynamic modelling could also be used in the highly flood-susceptible zones to simulate potential inundation areas.

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