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ORIGINAL ARTICLE

Flash flood risk assessment for drainage basins in the Himalayan foreland of Jalpaiguri and Darjeeling Districts, West Bengal

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Abstract
Flash floods pose significant threats to the socio-economic development of the Jalpaiguri and Darjeeling Districts. These districts situated in the piedmont zone of Sikkim–Darjeeling and Bhutanese Himalayas suffer from the flash floods, and those cause tremendous loss of life and property more or less every year. This study assessed flash flood risk of watersheds of the Himalayan foreland of Jalpaiguri and Darjeeling Districts in support of mitigation planning. Different hydro-geomorphological setup controls the magnitude, frequency and distribution of flash flood like topography, geomorphology, geology and climatology of the area under study. Land use/land cover and soils also have an integral relationship with run-off generation in the watersheds. Thus, we adopted holistic approach considering the topographic, hydrological, climatological, geological, soil and land use/land cover factors to assess the relative susceptibility to flash floods of the watersheds of Himalayan foreland of Jalpaiguri and Darjeeling Districts. Jaxa 30m DSM, Landsat8 OLI/TIRS and Sentinel 2A satellite images, digitized drainage network, geological, rainfall, soil and geomorphological map were analysed in GIS environment to infer lithology, land use, hydrological soil type and watershed morphometrics. The morphometric parameters were used to assign the relative susceptibility of the watersheds to flash flood, applying the weighted sum average method. Soil Conservation Service rainfall–runoff model of USDA and synthetic unit hydrograph were used to infer the hydrological response of the basin including curve number, runoff depth, time of concentration, lag time, peak discharge, etc. Final flash flood risk map was achieved by the integration of both the susceptibility maps. Higher weightage was given to the susceptibility map produced from run-off modelling and synthetic hydrograph parameters. The result shows that 63% of basins are fall in the high to very high categories of flash flood risk, 28% under medium and only 9% in the low categories of flash flood risk. Accuracy of the model was assessed using the flood inventory coupled with field diagnosis of past flood damages and available records. The resulting flash flood risk map could be used by the planners to adopt mitigation strategies to reduce the severity of the flash flood hazard.

Keywords Flash floods · Watershed · Morphometric · Remote sensing · GIS · DSM

Introduction

Flash flood, a destructive natural hazard, is responsible for more than 5000 deaths annually on a global basis (Jonkman 2005; Grabs et al. 2010; Modrick and Georgakakos 2015). India is the second most flood-affected country in the world after Bangladesh and accounts for one-fifth of global deaths due to floods (Agarwal and Narayan 1991). Jalpaiguri and Darjeeling Districts, situated in the piedmont zone of Sikkim–Darjeeling and Bhutanese Himalayas, are frequently striking by floods and flash floods and those cause tremendous loss of life and property every year (Sarkar 2008). Flash floods, in general, are the result of interaction between two factors, viz. meteorological condition and topography or surface characteristics of the drainage basin in terms of geomorphology (Costa 1987; Youssef et al. 2009; Kharraz et al. 2012). Because of the rugged topography together with steeps slopes and high relief of the watersheds in the Himalayan foreland of Jalpaiguri and Darjeeling Districts, heavy rainfall during the monsoon often results in flash floods associated with diffuse landsliding debris flow and sediment transport (Sarkar 2008;

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Prokop and Walanus 2017). The sudden and steady rise of discharge in rivers, along with the huge bed load of rocks and their debris, makes flash floods more disastrous in this region (Mukhopadhyay 1982). The southernmost front of the Himalayan foreland of Jalpaiguri and Darjeeling Districts acts as the first orographic barrier to the humid south-west monsoon; hence, it experiences the highest annual rainfalls (more than 400 cm) and the most frequent heavy rains (up to 80 cm per day) in the whole of the Himalayan front (Starkel 1972; Starkel and Basu 2000; Prokop and Walanus 2017). Among the rivers of the Himalayan foreland of the Jalpaiguri and Darjeeling Districts, only the Teesta originates in the glaciated higher Himalayas, while Jaldhaka originates from lesser Himalayas. Other rivers originate from the Siwalik Hills mostly and drain small area, ranging from 5 to 150 sq. km and characterized with very short flow distance. Heavy rainfall during the monsoon in these small watersheds produces run-off several times higher compared to bigger catchments (Prokop and Walanus 2017). In addition to that, many of these rivers originate at the same hill, and hence during monsoon floods often occur simultaneously in many rivers and the river coalesce over the piedmont to form a single sheet of water. Hence, for the aforementioned geophysical situation, the district has a long history of sufferings from floods and flash floods. The district experienced the most devastating flash flood in 1968 in its history, when 1200 mm rainfall was recorded in the Himalayan margin and all the rivers coalesce to form a single flood sheet (Sarkar 2008). Others prominent flash floods that occurred in the district were 1972, 1980, 1993,1998, 2000, 2002, 2003, 2004, 2005, 2007, 2008, 2009, 2010, 2012, 2015, 2017, 2019. Although flash floods are not new phenomena to the district, recently problems related to flooding have been greatly increased. Human interference into the catchments in the form of settlement construction, deforestation and mining has aggravated the problems and encroaching of settlement into the floodplain further increases the severity of the flash flood hazard. However, the devastating nature of the hazard can be reduced by adopting management strategies (Bisht et al. 2018). Hence, there is a need for effective modelling to understand the problems and minimize the severity of the disastrous effect of flash floods (Youssef et al. 2011). But despite the hazardous behaviour of the rivers, when there are several good quality works found related to the geological and geomorphological evolution of landscape (Acharya 1989; Mukhopadhyay 1982; Mukul 2000; Chakraborty and Ghosh 2010; Chattopadhyay and Das 1979; Sinha Roy 1980; Starkel 1972; Starkel et al. 2008; Starkel and Sarkar 2014), the watersheds of this region have received little attention in respect to their hydrogeomorphological behaviour (Starkel and Basu 2000; Sarkar 2008). There is no attempt made until now to study the flash flood susceptibility of the watersheds. Perhaps, unavailability of the data is the main reason behind that. Although the major watersheds of this region are well-gauged, data are not readily available for academic or public research as these are trans-boundary rivers and subject to dispute (Gupta et al. 2010). This research tried to fill these research gaps by quantifying valuable drainage morphometric parameters and characterize the hydro-geomorphology of the watersheds using the computed parameters, run-off modelling and synthetic hydrograph. The main objective of the study is flash flood assessment of the basins of the Himalayan foreland of Jalpaiguri district using geomorphometric and hydrological parameters.

Morphometry is defined as the measurement and mathematical analysis of the configuration of the earth's surface and the shape and dimension of its landforms (Clarke 1966). Morphometric characteristics of a watershed control different geomorphological processes and the hydrological behaviour of a watershed (Moussa 2003; Nookaratanam et al. 2005; Romshoo et al. 2012). The quantitative analysis of the morphometric characteristic of watersheds is of immense importance in flood behaviour prediction (Patton and Baker 1976; Baker 1976), sediment yield estimation (Hadley and Schumm 1961), watershed prioritization for soil and water conservation (Ghosh and Saha 2015) and natural resource management. The hydrological response of a watershed can be interrelated with the physiographic characteristics of the watershed, such as size, shape, slope, drainage density, first-order stream frequency, basin relief, ruggedness number, etc. (Chorley 1969; Gregory and Walling 1973; Baker 1976; Patton and Baker 1976). Hence, the quantitative analysis of morphometric characteristics of watersheds provides hints that could be used to infer the hydrological behaviour of the watersheds (Angillieri 2012; Kabite and Gessesse 2018). Morphometric characteristics of a watershed can be analysed by measuring linear, areal and relief parameters like-stream order, stream length ratio, relative relief, relief ratio, ruggedness number, etc. (Nag and Chakraborty 2003; Sreedevi et al. 2009; Thomas et al. 2012; Magesh et al. 2013). These parameters have been successfully utilized by several workers to estimate the flash flood susceptibility of the watersheds (Alexander 1972; Baker 1976; Patton and Baker 1976; Ghoneim et al. 2002; Roughani et al. 2007; Diakakis 2011; Youssef et al. 2011; Romshoo et al. 2012; Bhatt and Ahmed 2014; Farhan et al. 2016; Masoud 2016; Bannari et al. 2017; Prasad and Pani 2017; Bisht et al. 2018; Mahmood and ur Rahman 2019; Wani et al. 2018). The geomorphometric characteristics of the basin determine the behaviour of water after rainfall reaching the basin surface. However, the portion of rainfall available for surface run-off is not only determined by the geomorphometric characteristics but also the infiltration capacity of rocks and soils, interception storage by the vegetation, antecedent moisture condition of the soil and land use properties of the surface of the watershed. Hence, for a comprehensive understanding

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of the hydrological response of the basins, several authors use run-off modelling and synthetic hydrograph parameters for ungauged basins or where data are not available. In the flood-prone areas, it is essential to calculate the different components of a stream hydrograph to predict the hydrological response of the river during a rainfall event (Abuzied et al. 2016). Several methods have been developed by engineers to estimate the discharge for an ungauged basin such as the rational method, Soil Conservation Service (SCS)-Curve Number method, Cook's method and unit hydrograph method. Many authors successfully used SCS run-off modelling (Gioti et al. 2013; Elkhrachy 2015; Sudhakar et al. 2015; Abuzied et al. 2016, Masoud 2016; Iosub et al. 2020) and Synthetic Unit hydrograph (Ghoneim et al. 2002; Romshoo et al. 2012; Sudhakar et al. 2015; Prasad and Pani 2017; Singh and Singh 2017) to estimate the hydrological response of the basins and evaluate the flash flood susceptibility of the basins in different parts of the world. For the present study, we adopted SCS run-off modelling method to estimate run-off depth for different basins for a 24-h event rainfall. Other hydrograph parameters such as basin lag and time peak discharge were calculated using the equations of Central Water Commission of India (CWC 1991).

In the present study, at first, the susceptibility to flash flood of the watersheds is estimated using the WSA method based on the rank values of the morphometric parameters. The hydrological response of the watersheds was estimated using the SCS runoff modelling and synthetic hydrograph parameters. Watersheds were also categorized into different susceptibility class using compound parameters rank of rainfall, run-off depth, and the synthetic hydrograph parameters (such as time to peak, time of concentration, peak flow rate etc.). Finally, the flash flood risk map was obtained by integrating both the susceptibility maps.

Several studies have used remote sensing and GIS techniques to extract various morphometric parameters of the drainage watersheds as these rapidly provide accurate information (Bhatt and Ahmed 2014; Jaiswal et al. 2014; Ghosh and Saha 2015; Kadam et al. 2019). In the present study, we extracted various morphometric parameters (Table 1) using JAXA DSM and Sentinel 2B Satellite images in the GIS environment.

Study area

The study area spread over the Sikkim, Darjeeling, and parts of Bhutan Himalayas and their respective piedmont zone, covering approximately 10,480 sq. km. The study area belongs to the steep and rugged Himalayan mountainous terrain in the Darjeeling District of West Bengal and state of Sikkim, India and western Bhutan and their respective piedmont zones, mainly situated in the Jalpaiguri and Darjeeling Districts of West Bengal, India (Fig. 1a). The study area encompasses parts of Lesser Himalayas and Higher Himalayas. The elevation of the study area ranges from 123 to 8590 m with increasing elevation from the south to the north. There are four physiographic zones fall within the study area; these are from north to south—1. Greater Himalayas, 2. Lesser Himalayas, 3. Siwalik Himalayas, and 4. Piedmont zone (Fig. 1b). The upper part of most of the watersheds lies in higher Himalaya's mountain zone,

Table 1 Data used in the study

Data	Acquisition	Source	Resolution/scale	Application
JAXA DSM	2014–2015	Japan Aerospace Exploration Agency (JAXA) (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm)	30-m spatial resolution	Morphometry, watershed delineation
Landsat 8 OLI/TIRS	2015	USGS Earth Explorer (https://earthexplorer.usgs.gov)	30-m spatial resolution	Land use and land cover
Sentinel 2A	2016	European Space Agency (ESA) (https://scihub.copernicus.eu/dhus/#/home)	10-m spatial resolution	Drainage network, morphometry geomorphological map
Rainfall	1988–2017	India Meteorological Department (IMD), Pune	0.25-degree spatial resolution	Run-off modelling
GPS, District disaster management plan	2012–2020	Field survey, S.D.O Mal Bazar	–	Flash flood inventory
Soil map	–	NBSS & LUP Regional Centre, Kolkata, and FAO (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/)	1:500,000	Hydrologic soil group
Geological map	–	Bhargava (1995), Long et al. (2011) and Ghosh et al. (2015)	1:250,000 and 1:500,000	Hydrologic soil group

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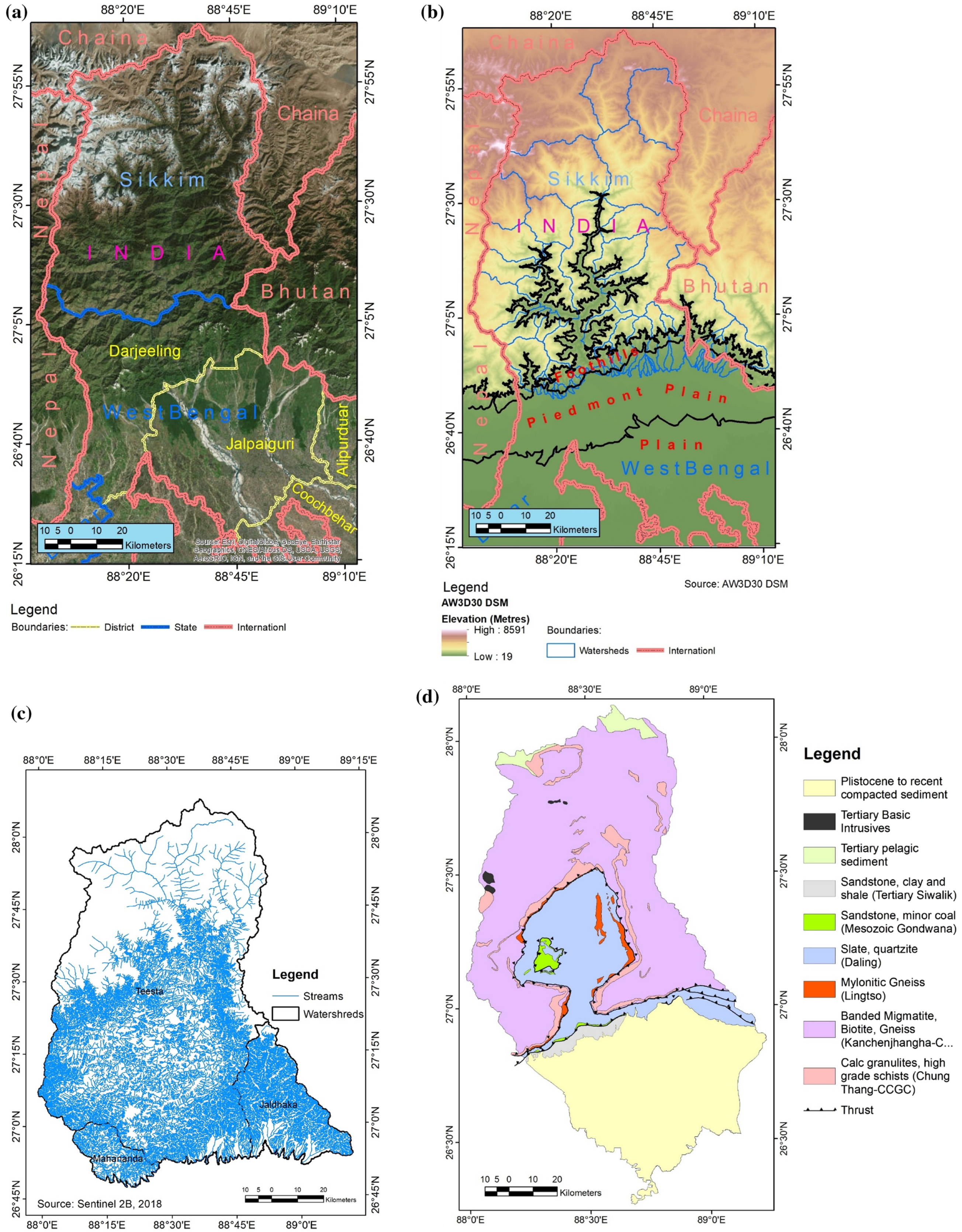

Fig. 1 **a** Location of the study area, **b** major physiographic divisions of the study area, **c** digitized drainage network of the SDBH with delineated major watersheds, **d** geological map of the study area (after Bhargava 1995; Long et al. 2011; Ghosh et al. 2015)

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including Greater and Lesser Himalayas, the middle part in the foothills and the lower part in piedmont. The higher Himalayas mountain zone is characterized by rugged terrain, high elevation and relief, steep slope and numerous streams. Piedmonts which are formed by the influence of permeable geology are characterized by very low relief and low drainage density.

The study area is drained by two mighty rivers, namely Teesta and Jaldhaka. The entire Sikkim and central and broader parts of the eastern Darjeeling fall under the Teesta catchment. Western parts of Darjeeling are drained by Mahananda and its tributaries, while Western Bhutan is drained by Jaldhaka and its tributaries (Fig. 1c). It is the piedmont zone of these mountainous streams which suffered most from different types of hydrogeomorphic hazards, where the mountainous stream charged with heavy sediment loads suddenly debouch on to the plains and lose their slope.

Geologically, the study area is the part of the world's youngest and active folded mountain system—the Himalayas and its piedmont zone. Several thrusts bounded litho-tectonic units controlling the geology of the area (Fig. 1d). The several tectonic units of the Sikkimese–Bhutanese Himalaya over-thrust towards the south are built mostly of metamorphic rocks (Darjeeling gneisses, Daling schist and quartzite, Damuda sandstone with quartzite and shale). The Main Boundary Thrust separates them from the Siwaliks built of sandstones, conglomerates and mudstones, which are overthrust over the Quaternary foredeep along the Himalayan Frontal Thrust. In the study area, the Siwalik belt is partly missing after the Chel river watershed (Starkel et al. 2008). The foreland of the Himalaya, the piedmont is built of Quaternary sediments and influenced by permeable geology.

Flash flood is one of the most recurrent hydro-meteorological hazards in the study area (Sarkar 2008). Human interference into the catchments in the form of settlement construction, deforestation and mining has aggravated the problems and encroaching of settlement into the floodplain further increases the severity of the flash flood hazard.

Data use and methodology

Data

The rivers traversing the Jalpaiguri and Darjeeling Districts are highly susceptible to flash flood due to the combined effect of their geophysical environment. Thus, we adopted a holistic approach to access their flash flood susceptibility considering the physiography, hydrology, meteorology, soil, land use/land cover, the geology of the study basins. Figure 2 illustrates our assessment methodology with data used from the sources tabulated in Table 1.

Methodology

Morphometry

ArcHydro 10.3 was used to delineate the watersheds using Jaxa 30m DSM. A threshold value of 0.36 sq. km was used for extraction of stream network as proposed by Tarboton et al. (1991), and watersheds were extracted applied this stream network using the pour points at the intersection of mainstreams and railway line crossing the piedmont zone of Jalpaiguri District. Besides this, Teesta basin spreading over Sikkim and Darjeeling Himalayas divided into sub-basins. Total 57 sub-watersheds were delineated within the Himalayan foreland of Jalpaiguri District. For the present work, we have selected different morphometric parameters (Table 2) which governs the hydrological response of a basin. The drainage network parameters, such as bifurcation ratio (Rb), drainage density (Dd), stream frequency (Sf), texture ratio (Rt) drainage intensity (Di) significantly contribute to the hydrological response of a watershed (Horton 1945; Schumm 1956; Strahler 1956; Patton and Baker 1976; Prasad and Pani 2017). The relief parameters, such as relief (H), relief ratio (Rr), slope (As) and ruggedness number (Rn), play a significant role in hydrological response of a catchment and its run-off generation and flow accumulation (Schumm 1956; Patton and Baker 1976). The catchment shape could determine the peakedness of the run-off hydrograph and thus flash flood susceptibility (Chorley 1969).

Thus we had adopted basin elongation ratio (Re) to measure the shape of the watershed. To come up with Rb, at first, the drainage network was ordered for each watershed applied the Strahler's Stream Segment method (1956) and the number of streams of each order was calculated and Rb for each order was obtained by applying the Horton's Rb formula (Table 2) and finally, the average Rb was obtained for each watershed. To calculate the drainage morphometric parameters, such as Dd, Sf, Rt and Di, the different equations developed by Horton (1945), Strahler (1956) and Faniran (1968) were applied on drainage network digitized from Sentinel 2B satellite images. The H, Rr, As and Rn were calculated using the formula mentioned in Table 2. Schumm's elongation ratio (1956) is adopted to estimate the shape of the basins. All the morphometric parameters considered in the study have a positive correlation with run-off generation. Higher the values of these parameters, greater will be the run-off generation. Hence, the highest value of these parameters was ranked 57, the second-highest value ranked 56, and so on. After ranking of morphometric parameters, the correlation matrix was prepared using the WSA method in Microsoft Excel and the sum of correlation was calculated. In the modified WSA method, first of all, the sum of correlation was calculated for each morphometric parameter. Further, the sums of correlation of all the parameters were

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Fig. 2 Flowchart of the flash flood risk assessment

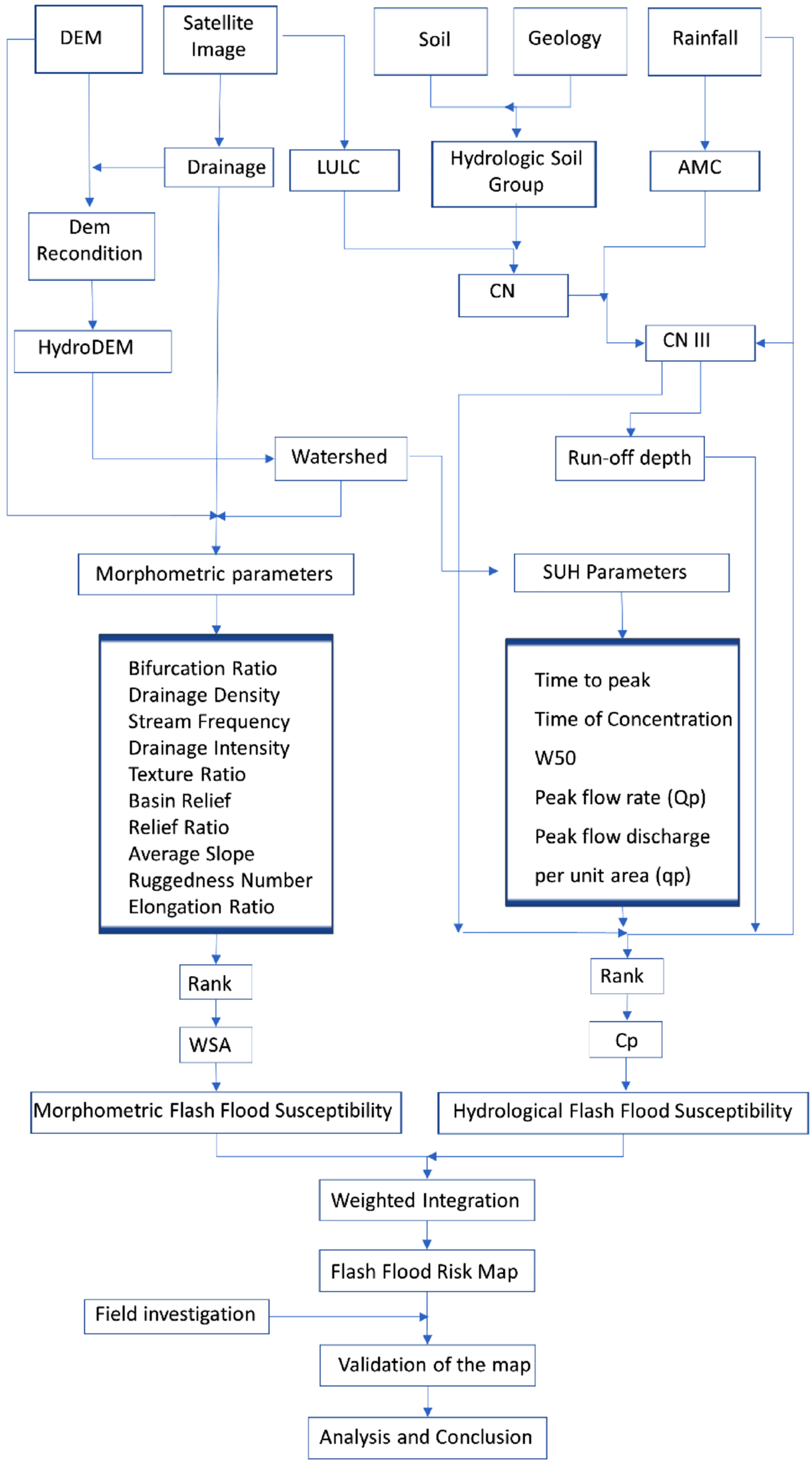

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Table 2 Mathematical expression and hydrological significance of morphometric parameters

Variables	Where used or defined	Formula	Units	Significance
Stream order	Strahler (1957)	1 + 1 = 2	Enumerative	Indicates size, the scale of the watershed and amount of stream flow
		2 + 1 = 2		
		2 + 2 = 3 and so on		
Bifurcation ratio (Rb)	Horton (1945)	Number of stream/number of stream of next higher order	Dimensionless	Represents the structural control on drainage pattern and influence the hydrological behaviour of the drainage network
	Strahler (1957)			
	Chorley (1969)			
Drainage density (Dd)	Horton (1945)	Total stream length/area of the watershed	km/km^2	Influences the output of discharge from the watershed
	Patton and Baker (1976)			
Stream frequency (Sf)	Horton (1945)	Total no. of stream/area of the watershed	No./km^2	Implies watershed permeability and surface runoff
Drainage intensity (Di)	Faniran (1968)	Drainage frequency/drainage density	Dimensionless	Indicates the efficiency of run-off removal capacity of the watershed
Texture ratio (Rt)	Smith (1950)	Total no. of stream segment/perimeter of the watershed	No./km	Reflects the permeability and runoff characteristics of the watersheds
Basin relief (H)	Strahler (1952), Schumm (1956), Melton (1957)	Highest elevation–lowest elevation	Linear (m)	Determines the stream gradient and influences the flood pattern
Relief ratio (Rr)	Schumm (1956)	Watershed relief/watershed length	Dimensionless	Represents overall steepness of the watershed
Average slope (As)	NRSC	(Contour length, in feet * contour interval, in m * 100)/area, in acres * 43,560	Degree	Overall slope of the watershed
Ruggedness number (Rg)	Melton (1957)	Drainage density * (Watershed relief/1000)	Dimensionless	Measure the flash flood potential of the watershed
	Patton and Baker (1976)			
Elongation ratio (Re)	Schumm (1956)	$R_e = (2\sqrt{(A/\pi)})/L_b$	Dimensionless	It measures the shape of the watershed and indicates the peakedness of the hydrograph

totalled to obtain the grand total. The final weight for each morphometric parameter was obtained with dividing the sum of correlation of each parameter divided by the grand total of sum of correlation.

Final Weight (Fwi) = Sum of correlation coefficient/Grand total of correlations

Finally, to estimate the susceptibility, compound parameters constant (CPC) was obtained for each watershed by summing up the product of the rank of each parameter with their corresponding final weight (Fwi). Watersheds with the highest CPC factor are of high priority, while that with lowest CPC is of low priority.

$$\mathrm{CPC} = \sum (P1r * \mathrm{Fwi}\, P1 + P2r * \mathrm{Fwi}\, P2 \cdots + Pnr * \mathrm{Fwi}Pn). \quad (1)$$

Run-off estimation

Rainfall and surface runoff is the most significant hydrological parameters for evaluation of basin susceptibility to flash flood hazard (Shadeed and Almasri 2010). The depth of surface run-off directly influencing the genesis of surface run-off (Mahmood and ur Rahman 2019). Rainfall–runoff modelling establishes the relationship between the rainfall and runoff to determine the flash floods susceptible basins (Abuzied et al. 2016). The SCS-CN method allows identifying the watersheds with a high risk of generating flood. Characteristics of surface hydrological processes are essential criteria for modelling flash flood hazards (Abuzied et al. 2016) because it governs the hydrological response of

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a basin during a storm event. These characteristics include runoff depth (Q), peak time (T_p), time of concentration (T_c) and peak discharge rate (Q_p). And these hydrological responses of drainage basin depend not only on the morphometric properties but also on the soil, land use/land cover and climatic characteristics of the watersheds. Hence, morphological parameters should be integrated spatially with soil, land use/land cover, and climatic parameters to evaluate the flash flood risk zone. SCS-CN method efficiently combined these parameters to estimate the hydrological response of ungauged basins, and this method has been successfully applied in different parts of the world for flash flood estimation (Gheith and Sultan 2002; Gioti et al. 2013; Wakode et al. 2013; Elkhrachy 2015; Sudhakar et al. 2015; Abuzied et al. 2016, Masoud 2016; Mahmood and ur Rahman 2019; Iosub et al. 2020). To estimate the catchment runoff, SCS-CN method requires information on numeric catchment characteristics related to DEM, land use/land cover (lulc), hydrologic soil groups and rainfall data. These data can be easily derived from the Remote Sensing product and efficiently used in the GIS environment to estimate SCS-CN runoff. To derive the lulc (Fig. 2) of the study area, LANDSAT OLI 8 level 2 images were classified in ERDAS 2011 using the supervised maximum likelihood method. The accuracy of the classified images is done with reference to high-resolution Google Earth images and field verification using the Kappa coefficient technique. The SCS-CN method relies on the hydrological properties of the soil. The soil map for the present study is obtained from the NBSS & LUP, Government of India, Kolkata, and for the portion of Bhutan Himalayas the soil map is downloaded from the website of FAO. The soil is classified into four hydrologic soil groups, viz. A, B, C and D. The Quaternary deposits in the downstream reaches of the watersheds, over the piedmont region, characterized with deep very well-drained soil that has high infiltration rate and low runoff potential are classified as A group. The second major HSG is B (silt, gravel sand), and it has low to moderate run-off. C and D group soils are developed over highly metamorphosed and igneous rocks having low infiltration capacity and high surface runoff. To estimate the run-off depth, SCS model requires Curve number (CN) value. The curve number (CN) is an empirical parameter used in basin hydrology for estimation of direct runoff from rainfall excesses (USDA Soil Conservation Service 1972). CN value exhibits the infiltration capacity of the soil and determines the portion of rainfall available as surface runoff (Mishra et al. 2003). High CN value means low infiltration, thus runoff and vice versa. Generally, CN values are defined based on a function of antecedent moisture condition (AMC), hydrological condition, land use and hydrologic soil type. AMC is estimated based on the total rainfall in the 5 days before a storm. The CN value was obtained by using the pairs of the combination of hydrologic soil group (HSG) and land use and land cover (LULC). There is more than one pair of the combination of HSG and LULC in each basin. Hence, we calculated the area-weighted CN value for each catchment. To obtain the daily rainfall depth in each catchment, 0.25° gridded rainfall data provided by the Indian Meteorological Department (IMD), Pune, for the entire study area were interpolated using IDW in ArcGIS then Zonal Statistics as Table tool is applied over the interpolated daily rainfall map with the watersheds shapefile.

Finally, the run-off depth for each basin was determined using the following equation:

$$Q = \frac{(P - 0.2S)2}{(P + 0.8S)} \tag{2}$$

where Q = run-off depth, P = total rainfall, $S = S$ is potential maximum retention after run-off begins (mm).

The maximum retention S is further related to the soil and land-cover conditions of the processed sub-basins through CN by the following equation:

$$S = \frac{25,400}{\mathrm{CN}} - 254 \tag{3}$$

Although SCS method is effective in the estimation of CN and runoff depth (Q) and successfully applied in several studies, it is not appropriate to estimate the peak flow rate (Q_p), peak discharge per unit area (q_p), time to peak (T_p), time of concentration (T_c) and width of the unit hydrograph at 50% height of peak flow discharge (W_{50}) for the mountainous watersheds as it was developed based on the geomorphometric characteristics of small agricultural watersheds. To calculate the Q_p, q_p, T_p and W_{50}, we used the equations of synthetic hydrograph of Central Water Commission of India (1991) which was developed for this particular region, as suggested by the scientists and engineers of Mal and Jalpaiguri Sub-divisional Irrigation Office, Government of West Bengal. They are the local authorities for monitoring and managing of riverine hazards in these areas, and they also rely on the design discharge data to construct flood protection measures and structures (spurs, embankments etc.). Furthermore, we used the equation of Verstappen (1983) to calculate the time of concentration (T_c).

Synthetic unit hydrograph

The synthetic unit hydrograph refers to a hydrograph of unit duration for a catchment under study obtained from the relationship established between the physiographic and the hydrograph parameters of the representative catchment in a hydro-meteorologically homogenous region (CWC 1991). Unit hydrograph parameters such as the Q_p = peak flow rate, peak discharge per unit area (q_p), time of concentration (T_c), time to peak (T_p) and width of the hydrograph at 50% peak

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discharge (W_{50}) influence the safe and peak of the hydrograph and thus determine the flash flood susceptibility (Snyder 1938; Chow et al. 1988; Prasad and Pani 2017). Peak discharge rate (Q_p) is the highest point on the hydrograph when the rate of discharge is greatest. It is determined by watershed characteristics, such as drainage density, slope, and flow path length. (Ramírez 2010). Time of concentration (T_c) is defined as the time taken by the water to flow from the most distant point to the outlet of the watershed (Haan et al. 1994). It is used in basin hydrology to measure the response of a watershed to a rainfall event. The watershed characteristics such as length and slope together with the hydraulic characteristics of the flow path determine the time of concentration (Ramírez 2010). Time to peak discharge (T_p) refers to the time to reach the peak value in a hydrograph.

Several techniques have been developed to estimate the unit hydrograph and its different features of ungauged basins based on the information of catchment characteristics. Snyder was the first to develop a synthetic hydrograph (Chow et al. 1988). Snyder (1938) developed a set of empirical relations between the different components of a hydrograph, viz basin lag time (T_p), peak flow rate (Q_p) and peak discharge per unit area (q_p) and geometry of catchment-based on a study of 20 drainage basins hydrographs ranging from 30 to 3000 square kilometre in area, located in Appalachian Highlands of the United States (Chow et al. 1988; Ramírez 2010). The Central Water Commission (1991) of Government of India took a similar approach to derive the relationship based on a linear regression between parameters of unit hydrograph and geometry of basins for different hydro-meteorological regions of the country. They studied 29 gauged watersheds of North Brahmaputra region to estimate the relationship among different parameters of unit hydrograph and watershed geo-morphometric characteristics. As our study area falls within the North Brahmaputra region, we adopted the CWC (1991) empirical equations in our study. CWC (1991) found the following relations between different components of unit hydrograph and basin geometry:

$$q_p = 2.272\,(L\,L_c/S)^{-0.49} \tag{4}$$

$$T_p = 2.164\,(q_p)^{-0.94} \tag{5}$$

$$W_{50} = 2.084\,(q_p)^{-1.065} \tag{6}$$

$$Q_p = q_p * A \tag{7}$$

Furthermore, we used the following equation of Verstappen (1983) to calculate the time of concentration (T_c):

$$T_c = 6.95(L^{1.15}/H^{0.385}) \tag{8}$$

where q_p = peak flow discharge per unit area, L = longest length of stream flow path, L_c = length along the mainstream from the gauging station to a point opposite the centroid of the watershed, S = slope of the basin in m/km, t_p = time to peak discharge, W_{50} = width of the unit hydrograph at 50% height of peak flow discharge. Q_p = peak flow rate, A = watershed area in sq. km, T_c = time of concentration, H = basin relief.

To derive the synthetic unit hydrograph for the watersheds, the data such as area (A), longest length of stream flow path (L) and length along the mainstream from the gauging station to a point opposite to the centroid of the watershed (L_c) are calculated in ArcGIS software using the Arc Hydro tool. To calculate the slope, we used DEM to extract the elevation.

Results and discussion

The predicted flash flood risk map is derived from the morphometric analysis, SCS-CN rainfall–run-off estimate, basins' synthetic hydrographic properties and field diagnosis. The method used the topographic, hydrology, soil, land use/land cover and climatic characteristics in a comprehensive manner.

Morphometric analysis

For the present work, authors have selected different morphometric parameters (Table 2) which govern the hydrological response of a basin. The result of the morphometric parameters is presented in Table 3. The morphometric results confirmed with field study have been analyzed below. The parameters, such as H, Rr, Rb, Dd, Sf, Rt, Din, As, Rg and Re generally, have a positive correlation with run-off generation. Higher the values of these parameters, greater will be the run-off generation and thus higher flood risk (Prasad and Pani 2017). The drainage network parameters, such as bifurcation ratio (Rb), drainage density (Dd), stream frequency (Sf), texture ratio (Rt) drainage intensity (Di) significantly contribute to the hydrological response of a watershed. Bifurcation ratio (Rb) is an important control over the 'peakedness' of the run-off hydrograph (Chorley 1969). The higher value indicates early attainment of hydrograph peak with a potential for flash flooding during intense rainfall events (Rakesh et al. 2000; Kanth and Hassan 2012). Results of Rb value (Table 3) analysis revealed that most of the Himalayan sub-watersheds exhibit moderate to high Rb values (Fig. 3a), which indicate high overland flow and discharge due to hilly terrain plus steeper disposition of slopes (Ozdemir 2012). Drainage density (Dd) is one of the important factors that controlling the surface runoff and consequently influences the output of discharge from

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Table 3 Morphometric parameters of watersheds

Watershed	Rb	DD	Sf	Rt	Di	H	Rr	As	Rg	Re
Andhi jhora	6.83	5.36	16.57	3.49	3.09	372	0.09	32.99	0.52	0.49
Balasan	5.66	3.21	4.63	11.62	1.44	2339	0.10	45.80	5.82	0.78
Chaiti	2.00	1.31	0.54	0.21	0.41	185	0.02	6.53	5.15	0.43
Chel	3.91	4.21	9.21	11.48	2.19	2310	0.09	41.72	0.35	0.49
Chhombo Chhu	3.98	0.28	0.08	0.26	0.28	4416	0.08	53.55	11.32	0.71
Choklong Khola	4.62	2.54	3.82	1.42	1.50	560	0.12	40.62	7.05	0.61
Churanthi	3.90	5.08	17.95	5.64	3.53	1013	0.11	42.85	1.42	0.38
Demka Jhora	3.50	2.96	2.27	0.73	0.77	119	0.02	7.04	1.58	0.50
Diana–Chamurchi	3.50	3.69	6.89	14.35	1.87	3272	0.13	53.93	12.38	0.72
Dik Chhu	4.29	3.52	7.16	16.27	2.04	4656	0.16	51.72	12.06	0.62
Ghatia	4.16	3.63	6.77	4.55	1.87	2346	0.12	29.01	2.55	0.39
Ghatia sub	3.16	2.39	1.87	0.52	0.78	344	0.04	6.87	2.17	0.40
Ghish	4.12	3.89	7.99	11.77	2.05	2199	0.09	44.73	0.59	0.56
Ghoramara Khola	5.00	3.68	5.74	1.68	1.56	635	0.19	37.60	7.64	0.72
Gulma Khola	4.02	3.69	6.95	3.89	1.88	723	0.14	53.26	15.76	0.73
Gurujong Khola	3.00	2.71	2.86	0.57	1.05	138	0.02	8.70	3.90	0.35
Jaldhaka	4.24	4.73	9.47	33.90	2.00	4422	0.09	52.83	0.75	0.61
Kalej Khola	3.75	2.66	3.73	7.48	1.40	3363	0.13	59.84	1.37	0.66
Kali Khola	3.50	2.05	1.24	0.56	0.60	366	0.04	8.38	8.56	0.47
Kaligaiti	3.64	3.73	8.77	3.70	2.35	581	0.18	36.54	5.90	0.90
Kuji Diana	3.50	4.12	10.43	10.51	2.53	1709	0.11	33.36	0.69	0.53
Kumlai	3.75	2.89	1.42	0.49	0.49	180	0.02	8.62	7.33	0.42
Kurti	3.58	2.88	2.13	1.05	0.74	549	0.04	9.03	1.62	0.38
Kurti Nadi	4.00	1.92	1.95	0.55	1.02	305	0.04	8.81	0.73	0.37
Lish	4.60	4.26	10.23	9.29	2.40	1722	0.12	51.41	8.51	0.57
Mahananda	3.43	3.40	6.06	8.31	1.78	2073	0.12	54.27	1.67	0.64
Mal	4.10	3.81	8.48	6.61	2.23	1302	0.09	25.70	13.38	0.50
Mid Teesta Basin	3.05	2.47	3.25	9.61	1.32	3707	0.05	81.85	0.36	0.50
Murti	4.35	3.35	4.46	4.96	1.33	2370	0.10	27.56	9.71	0.48
Neora	5.59	4.45	8.96	10.81	2.01	3003	0.10	40.42	1.99	0.44
Nidim Jhora	3.00	2.99	1.18	0.19	0.40	120	0.02	7.93	2.21	0.31
Prek Chhu	4.03	1.49	2.17	6.40	1.46	5131	0.23	74.62	11.61	0.88
Rakti Khola	3.44	1.97	3.08	1.55	1.56	1704	0.18	44.70	0.37	0.50
Raman Khola	3.54	4.29	8.97	25.89	2.09	3369	0.09	63.53	12.02	0.76
Rambi Khola	3.95	4.35	8.94	15.78	2.06	2763	0.10	75.57	0.82	0.58
Ramthi	6.43	4.22	10.20	6.77	2.42	1195	0.11	45.28	20.92	0.52
Rangit Khola	4.60	2.23	2.56	6.11	1.15	3027	0.10	68.44	1.23	0.68
Rangyong Chhu	3.37	1.47	1.81	7.63	1.23	7697	0.17	58.97	14.45	0.75
Rani Khola Chhu	4.05	2.67	4.31	10.63	1.61	4348	0.15	56.52	4.96	0.62
Rathang Rimbi Khola	3.60	3.95	7.50	19.29	1.90	3985	0.12	55.68	1.38	0.68
Reli Khola	3.62	2.66	3.46	6.62	1.30	2190	0.09	60.55	4.93	0.63
Relli Chhu	4.31	3.43	5.98	16.66	1.74	4889	0.30	49.93	9.17	0.94
Rohini Khola	2.99	2.96	4.76	2.54	1.61	1665	0.16	42.51	0.24	0.48
Rong dong	4.71	4.34	8.92	5.55	2.06	588	0.11	42.38	12.30	0.80
Rongpo Rangli Khola	3.70	2.77	4.53	14.41	1.63	4434	0.11	58.45	7.04	0.66
Rongsung Khola	3.83	1.98	2.34	1.02	1.18	843	0.19	33.24	1.76	0.69
Rongtong Khola	3.55	2.76	4.57	2.77	1.65	496	0.09	31.78	16.78	0.72
Shevok Khola	4.60	3.80	7.30	4.69	1.92	1025	0.16	57.33	8.95	0.73
Sukhani Jhora	3.60	2.70	2.27	0.67	0.84	254	0.03	9.49	2.34	0.39
Sukna Jhora	4.90	2.50	3.72	1.36	1.49	651	0.09	32.69	5.04	0.47
SuknaJhora Sub	4.00	1.92	3.27	0.91	1.70	379	0.08	22.66	7.95	0.51

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Table 3 (continued)

Watershed	Rb	DD	Sf	Rt	Di	H	Rr	As	Rg	Re
Teest Upper	4.73	2.56	3.64	14.34	1.42	4831	0.13	57.79	6.79	0.93
Teesta sub	4.50	3.35	10.18	2.33	3.04	659	0.31	58.94	2.67	0.68
Teesta Sub 1	4.71	3.10	4.76	3.75	1.54	1905	0.17	68.95	7.52	0.63
Teesta Sub 2	3.96	2.94	4.64	6.18	1.58	2307	0.14	53.22	3.36	0.67
Yumthang Chhu	4.45	0.43	0.14	0.52	0.32	4143	0.12	53.42	16.39	0.88
Zemu Chhu	4.00	0.23	0.07	0.26	0.29	5906	0.13	57.51	6.75	0.77

the watershed (Chorley 1969) and thus a measure of watershed efficiency in removing excess precipitation inputs (Patton and Baker 1976). A high Dd implies a relatively rapid hydrologic response of the watershed to rainfall and vice versa (Melton 1957). Thus flood-prone regions are characterized by high Dd values (Patton and Baker 1976). In the present investigation, the Dd value maximum in Andhijhora (6.31 km/km^2) and minimum in Zemu Chhu (0.23 km/km^2). Watersheds lying in middle and lower Himalayas exhibit moderate (2.5–3.5 km/km^2) to high (3.5–4.5 km/km^2) Dd (Fig. 3b). Stream frequency (Sf) is an interlinking factor in predicting flood discharge (Patton and Baker 1976; Eze and Efiong 2010). Generally, the high value of Sf is related to impermeable subsurface material, sparse vegetation and low infiltration capacity (Reddy et al. 2004; Shaban et al. 2005). Thus, higher Sf points to larger surface runoff (Pakhmode et al. 2003). For the present study, Sf varies from 0.67/km^2 for Zemmu Chhu to 17.95/km^2 for Churanthi (Fig. 3c). Drainage texture ratio (Rt) is defined as the ratio of the number of first-order streams to the perimeter of the watershed (Smith 1950). Thus, it is a measure of relative spacing of the stream channel in a unit area along a linear direction (Howard 1967) which depends on the climate, rainfall intensity, vegetation, soil and rock type, infiltration rate, relief and the stage of development of the watershed (Smith 1950). Hydrologically very coarse texture watersheds have large watershed lag time periods (Angillieri 2008). Most of the mountainous catchments reveal intermediate to fine categories of Rt, which indicates moderate to high run-off. Rambi, Dik Chhu, Relli Chhu, Rathang Rimbi Khola, Raman Khola, and Jaldhaka manifest ultra-fine texture (Fig. 3d), which indicates very low permeability and very high runoff. Thus, hydrologically these watersheds have a shorter lag time. Drainage intensity (Di) measures the efficiency of runoff removal capacity of the watershed surface. Higher the values of Di lower will be the water storage in the watersheds during rainfall and thus increase the risk of flooding at their downstream reaches during heavy downpours. Watersheds with higher values of Di have greater chances to have flooding in their downstream reaches, whereas watersheds with lower values of Di have a greater chance to cause flooding within the watershed. Thus, a lower value of Di is an indication of water stagnation in the watershed. Most of the sub-watersheds of Teesta and Jaldhaka are exhibiting moderate to very high values of Di (Fig. 3e), which suggests that these watersheds are very efficient in the removal of run-off from the surface during intense rainfall, which in turn make their downstream reaches very susceptible to flooding.

The topographical characteristics of a watershed, such as relief, relief ratio, slope and ruggedness number play a significant role in hydrological response of a catchment and its run-off generation and flow accumulation (Schumm 1956; Patton and Baker 1976). Relief (H) determines the stream gradient and influences the flood pattern (Hadley and Schumm 1961). With increasing relief, steeper hill slopes and higher stream gradients, time of concentration of runoff increases, thereby increasing flood peaks (Patton and Baker 1976). Analysis of relief of the present study reveals that most of the sub-watersheds are characterized with very high relief (Fig. 3f), which indicates their high potentiality for flooding. Relief ratio (Rr) is a measure of the overall steepness of a watershed and a good indicator of the intensity of the erosional process operating on the slope of the watershed (Schumm 1956). The higher Rr value indicates the shorter Lag time and attains higher peak discharge and flow velocities (Bhatt and Ahmed 2014). The Rr varies between 0.018 for Nidim Jhora to 0.31 for Teesta sub. (Fig. 3g).

Slope is one of the important morphometric parameters that govern the flood response of a watershed. Watershed with steep slopes has high surface runoff (Prasad and Pani 2017). In the present study, the average slope for the watersheds ranges from 6.53° to 81.85° (Fig. 3h). The high average slope in the watersheds with shorter length of overland flow and quick water flow into the streams contributing to hydrograph rise (Samal et al. 2015). Ruggedness number (Rns) is the product of drainage density and basin relief which combines slope steepness with its length (Strahler 1954). Patton and Baker (1976) opined that watershed with highest Rns incorporating a fine drainage texture, with a minimal length of overland flow across the steep slope and high channel gradients might be expected to high flood potential. The Rg ranges from 0.25 for Rohini Khola to 20.92 for Ramthi Khola (Fig. 3i). Most of the watersheds in the present study are categorised with high to very high values of Rg that suggest high susceptibility to flash flood.

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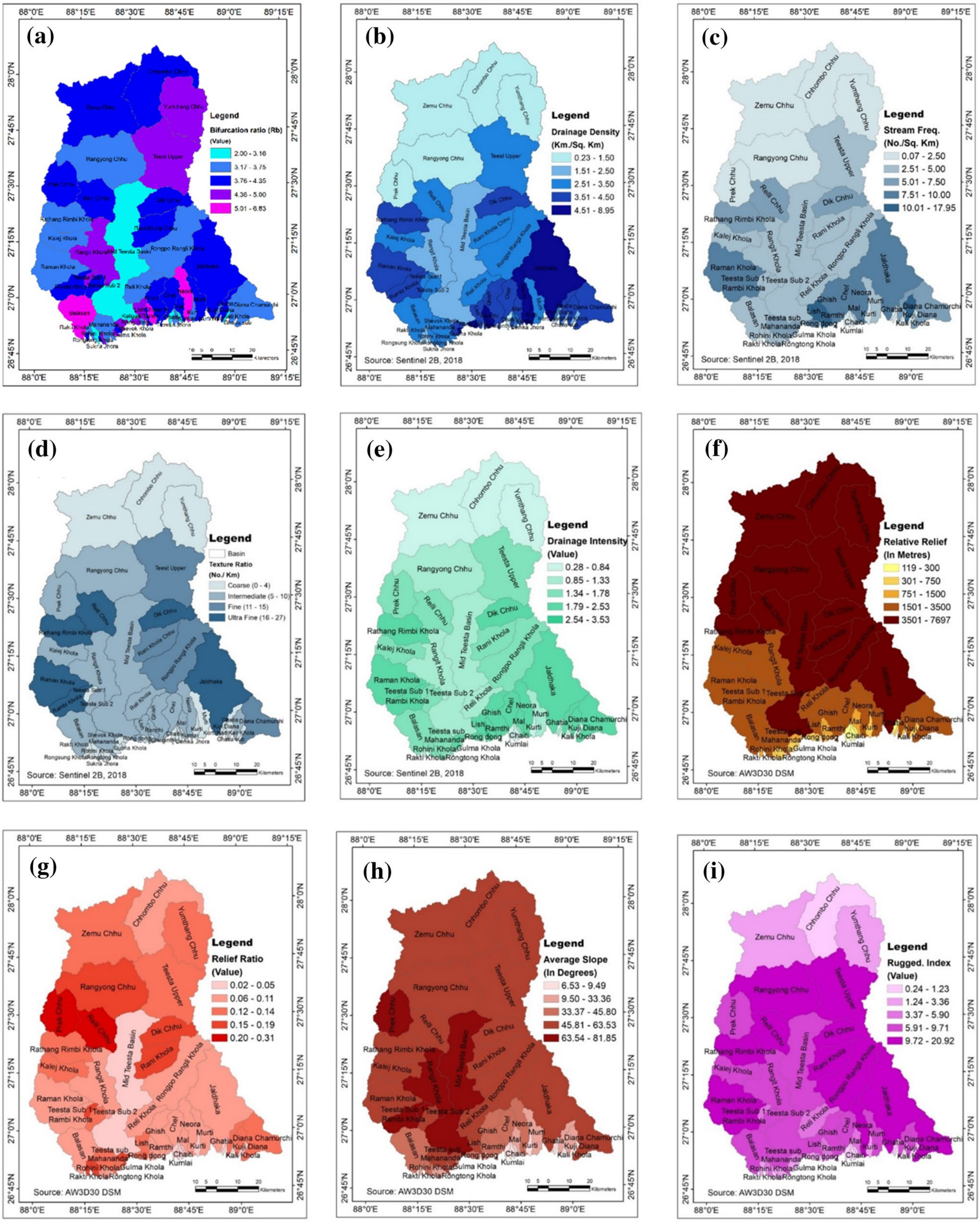

Fig. 3 Morphometric parameters: **a** bifurcation ratio, **b** drainage density, **c** stream frequency, **d** texture ratio, **e** drainage intensity, **f** relative relief, **g** relief ratio, **h** average slope, **i** ruggedness index

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The catchment shape could influence drainage efficiency and thus flash flood susceptibility. Elongation ratio (Re) is one of the indices to measure the shape of the watershed. It is defined as the ratio of the diameter of a circle of the same as the watershed to the maximum length of the watershed (Schumm 1956). The ratio generally ranges between 0.6 and 1.0. Watershed elongation directly affects the amount of peak discharge and its arrival time at the outlet of watersheds. A circular watershed is more efficient in run-off generation than an elongated watershed (Sreedevi et al. 2009), and have a shorter lag time in hydrograph peak. The Re ranges from 0.31 for Nidimjhora to 0.94 for Relli Chhu. Most of the Himalayas watersheds have Re values of greater than 0.5 which suggests that these are more circular than elongated. Thus indicates high susceptibility to flooding.

Watershed morphometry and flood status of the watersheds

The flooding behaviour of a given watershed could be predicted from morphometric parameters like basin shape, drainage density, drainage frequency, texture ratio, ruggedness number, average slope, basin relief and relief ratio (Baker 1976; Patton and Baker 1976; Ghoneim et al. 2002; Youssef et al. 2011; Romshoo et al. 2012; Bhatt and Ahmed 2014; Farhan et al. 2016; Prasad and Pani 2017; Bisht et al. 2018; Mahmood and ur Rahman 2019). Very high average slope, ruggedness number and relief ratio, high to very high relief, medium to high drainage density and stream frequency values of Himalayan watersheds make them more flood-prone. More or less every year the downstream reaches of these watersheds suffer from the flash floods. So problematic watersheds need to be identified for implementation of various flash floods hazard management practices. The flash flood susceptibility for the drainage basins in the Himalayan foreland of Jalpaiguri District is determined according to rank values of the morphometric parameters in each basin applied the Weighted Sum Average (WSA) method. All the morphometric parameters considered in the study have a positive correlation with run-off generation. Hence, the highest value of these parameters was ranked 57, the second-highest value ranked 56 and so on. After ranking of morphometric parameters, the correlation matrix (Table 4) was prepared and the sum of correlation for each parameter was calculated. Subsequently, the weight of each parameter was estimated applying Eq. (1). The calculated compound parameter coefficient (CPC) values are incorporated in Table 5. This method provides a relative measure to identify basins of relatively high or low susceptibility to flooding. The greater the CPC value, the higher the susceptibility to flash flood and vice versa (Prasad and Pani 2017). The CPC value for the present study ranging from 5.05 to 44.57 signifies the relative combined geomorphometric susceptibility of the basin to flash flood. Based on CPC values, basins are grouped into 4 susceptibility categories (Fig. 4).

Relli Chhu, Raman Khola, Dik Chhu, Lish, Rambi Khola, Ramthi, Jaldhaka, Teesta sub, Shevok Khola, Rathang Rimbi Khola, Diana Chamurchi and Teesta upper are very highly susceptible to flash floods. These sub-basins pose very high drainage density, stream frequency, texture ratio, drainage intensity, average slope, relief and elongation ratio. Balasan, Mahananda, Gulma, Ghoramara, Kaligaiti, Churanthi, Andhijhora, Ghish, Chel, Mal, Neora, Ghatia and Kuji Diana fall under the highly susceptible category. These basins generally represent moderate drainage density and stream frequency, moderate to high drainage texture and drainage intensity, relief, average slope. All these parameters value are low to very low for moderate and low susceptible watersheds. In short, the flash flood susceptibility map shows that 23% of the total sub-watersheds have a very high possibility of flash flooding, 39% have high, 20% have moderate and 18% have a low possibility of flash flooding.

Table 4 Correlation matrix

Variables	Rb	DD	Sf	Rt	Di	H	Rr	As	Rg	Re
Rb	1.00	0.29	0.37	0.20	0.33	0.20	0.31	0.19	0.26	0.29
DD	0.29	1.00	0.90	0.56	0.82	−0.01	0.08	0.03	−0.09	−0.04
Sf	0.37	0.90	1.00	0.65	0.96	0.12	0.29	0.20	−0.08	0.10
Rt	0.20	0.56	0.65	1.00	0.62	0.66	0.33	0.58	−0.04	0.35
Di	0.33	0.82	0.96	0.62	1.00	0.12	0.35	0.21	−0.03	0.13
H	0.20	−0.01	0.12	0.66	0.12	1.00	0.48	0.77	0.13	0.55
Rr	0.31	0.08	0.29	0.33	0.35	0.48	1.00	0.53	0.20	0.62
As	0.19	0.03	0.20	0.58	0.21	0.77	0.53	1.00	0.08	0.63
Rg	0.26	−0.09	−0.08	−0.04	−0.03	0.13	0.20	0.08	1.00	0.47
Re	0.29	−0.04	0.10	0.35	0.13	0.55	0.62	0.63	0.47	1.00
Sum	3.44	3.53	4.52	4.92	4.51	4.01	4.19	4.22	1.90	4.11
Grand total	39.35	39.35	39.35	39.35	39.35	39.35	39.35	39.35	39.35	39.35
Weight	0.09	0.09	0.11	0.12	0.11	0.10	0.11	0.11	0.05	0.10

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Table 5 Primary ranking of watersheds based on the value of morphometric parameters and calculated CPC

Watershed	Rb	DD	Sf	Rt	Di	H	Rr	As	Rg	Re	CPC
Andhi jhora	57	57	56	23	56	10	20	17	5	17	32.81
Balasan	55	32	30	47	22	36	25	31	31	51	36.00
Chaiti	1	4	4	2	5	5	2	1	30	10	5.05
Chel	26	48	50	46	49	35	19	24	2	16	33.62
Chhombo Chhu	29	2	2	3	1	49	13	39	46	42	20.61
Choklong Khola	48	16	25	17	25	14	33	23	36	28	25.56
Churanthi	25	56	57	31	57	22	28	27	14	5	33.48
Demka Jhora	11.5	29	13	12	9	1	4	3	15	21	11.40
Diana Chamurchi	11.5	40	38	50	38	42	42	40	51	43	39.56
Dik Chhu	40	37	40	53	44	52	48	34	49	30	42.64
Ghatia	38	38	37	27	37	37	37	14	23	7	29.65
Ghatia sub	6	13	9	7	10	8	10	2	20	8	8.64
Ghish	37	45	43	48	45	33	18	29	6	25	34.66
Ghoramara Khola	53	39	34	19	27	17	54	21	39	44	33.72
Gulma Khola	33	41	39	26	39	20	43	37	54	46	36.76
Gurujong Khola	3.5	22	17	10	13	3	3	7	26	2	9.81
Jaldhaka	39	55	51	57	42	50	14	35	9	29	39.95
Kalej Khola	22.5	19	24	38	20	43	41	50	12	35	31.82
Kali Khola	11.5	11	6	9	7	9	9	5	42	13	10.41
Kaligaiti	20	42	45	24	51	15	51	20	32	55	35.93
Kuji Diana	11.5	47	55	43	54	28	31	19	7	24	34.14
Kumlai	22.5	26	7	5	6	4	5	6	37	9	10.73
Kurti	16	25	11	15	8	13	8	9	16	4	12.03
Kurti Nadi	31	8	10	8	12	7	7	8	8	3	9.97
Lish	46	50	54	41	52	29	36	33	41	26	40.82
Mahananda	8	35	36	40	36	31	38	41	17	34	33.08
Mal	36	44	44	35	50	25	17	12	52	20	32.50
Mid Teesta Basin	5	14	19	42	18	45	11	57	3	18	25.09
Murti	42	34	27	29	19	38	24	13	45	14	27.08
Neora	54	54	48	45	43	40	27	22	19	11	37.01
Nidim Jhora	3.5	30	5	1	4	2	1	4	21	1	6.01
Prek Chhu	34	6	12	34	23	55	55	55	47	53	36.94
Rakti Khola	9	9	18	18	28	27	52	28	4	19	22.59
Raman Khola	14	51	49	56	48	44	16	52	48	49	43.14
Rambi Khola	27	53	47	52	46	39	26	56	10	27	40.34
Ramthi	56	49	53	37	53	24	29	30	57	23	39.98
Rangit Khola	46	12	16	32	14	41	23	53	11	40	29.56
Rangyong Chhu	7	5	8	39	16	57	50	49	53	48	32.65
Rani Khola Chhu	35	20	26	44	31	48	45	43	28	31	35.78
Rathang Rimbi Khola	17.5	46	42	55	40	46	35	42	13	39	39.56
Reli Khola	19	18	21	36	17	32	21	51	27	33	27.85
Relli Chhu	41	36	35	54	35	54	56	32	44	57	44.57
Rohini Khola	2	28	32	21	30	26	46	26	1	15	24.38
Rong dong	49.5	52	46	30	47	16	32	25	50	52	38.98
Rongpo Rangli Khola	21	24	28	51	32	51	30	47	35	36	36.13
Rongsung Khola	24	10	15	14	15	21	53	18	18	41	23.05
Rongtong Khola	15	23	29	22	33	12	15	15	56	45	25.08
Shevok Khola	46	43	41	28	41	23	47	44	43	47	39.84
Sukhani Jhora	17.5	21	14	11	11	6	6	10	22	6	11.67
Sukna Jhora	52	15	23	16	24	18	22	16	29	12	21.83
SuknaJhora Sub	31	7	20	13	34	11	12	11	40	22	18.97

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Table 5 (continued)

Watershed	Rb	DD	Sf	Rt	Di	H	Rr	As	Rg	Re	CPC
Teest Upper	51	17	22	49	21	53	40	46	34	56	39.13
Teesta sub	44	33	52	20	55	19	57	48	24	38	39.86
Teesta Sub 1	49.5	31	33	25	26	30	49	54	38	32	36.24
Teesta Sub 2	28	27	31	33	29	34	44	36	25	37	32.96
Yumthang Chhu	43	3	3	6	3	47	34	38	55	54	26.25
Zemu Chhu	31	1	1	4	2	56	39	45	33	50	25.15

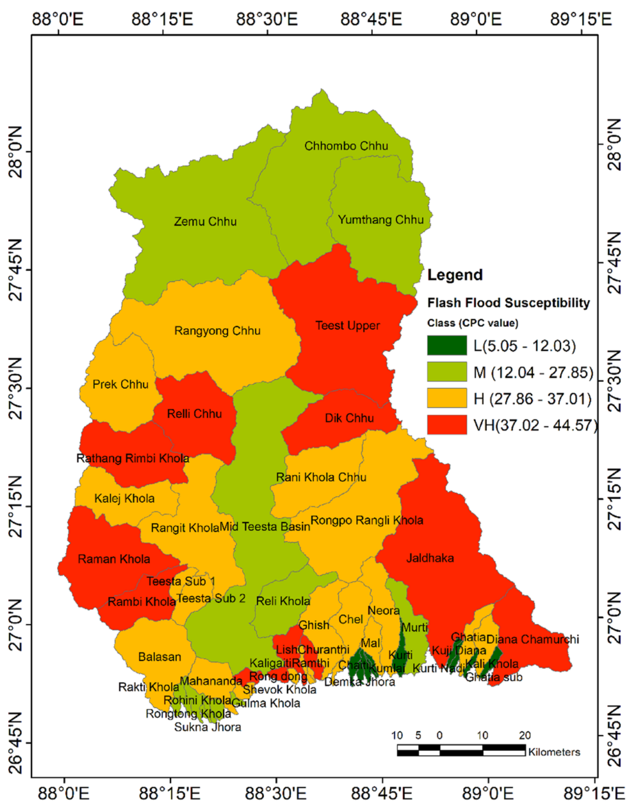

Fig. 4 Flood susceptibility map based on the morphometric parameters

SCS-CN rainfall–runoff modelling

The flash flood-prone basins were also assessed based on the analysis of runoff characteristics of the basins using SCS empirical equations. The event rainfall amount, land use and land cover and soils infiltration have an integral relationship with run-off generation in the watersheds. Rainfall and infiltration play a key role in run-off generation. The amount and intensity of rainfall are the most significant factors which determine the intensity and magnitude of the flash flood. In the Eastern Himalayan region, the spatial distribution of the total amount of rainfall and intensity of rainfall follows the same pattern (Starkel and Basu 2000; Prokop and Walanus 2017). We have the rainfall data at 24 h interval, so instead of the intensity of rainfall, we used monthly average rainfall of monsoon months (May–September) of last 30 (1988–2017) years and calculated basin-wise average rainfall for flash flood susceptibility assessment (Table 6; Fig. 5a).

The CN value is calculated using the lulc (Fig. 5b) and HSG (Fig. 5c) and transformed to AMC III condition. The high CN (Fig. 5d) values for most of the basins indicate high surface run-off. Higher CN values are found in Zemu Chhu, Yumthang Chhu, Prek Chhu, Chhombo Chhu, Rangyong Chhu and Rongsung Khola. These basins are characterised with bare earth, sparse forest, snow and glacier cover, steeper slopes and metamorphosed rocks. A combination of higher rainfall and low infiltration produces greater run-off and thus a higher flash flood risk. Most of the watersheds are fall under high precipitation zone (Fig. 5a) and consists of igneous and metamorphic rocks (Fig. 1d) coupled with very steep slopes having low infiltration rates and thus experience high run-off depths (Fig. 5f). The high values of run-off depth concentrate in Reli khola, Neora, Jaldhaka, Ghatia, Kuji Diana, Diana–Chamurchi.

Synthetic unit hydrograph

In the present study, the lowest class of lag time range from 1.90 to 6.50 h that suggests frequent flash flood because these have a very short time to reach a peak. These low values of lag time (T_p) are found mostly in the basin of uplifted fan surface of piedmont region. As these basins are very smaller in size, these do not generally produce a flash flood with larger magnitude. Some of the Lesser Himalayan watersheds like Mahananda, Lish, Churanthi, Ramthi, Mal, Kurti, Ghatia and Kuji Diana which are directly fall into the piedmont have medium lag time (T_p), ranging from 6.51 to 12.59 h, and, as these are comparatively larger in size, are very susceptible to flash floods. These rivers generally produce the frequent and comparatively larger magnitude of flash floods. Rivers like Balasan, Ghish, Chel, Neora, Murti and Diana–Chamurchi have a high time to peak (T_p), time of concentration (T_c), and W_{50} (Fig. 4g, h). These watersheds are larger in size ranging from 100 to 238 sq. km in area and these are situated in high rainfall zone. Due to high lag time, time of concentration and W_{50}, flash floods are not

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Table 6 Hydrological parameters of watersheds

Watershed	L	L_c	H	S	AmR (mm)	ER (mm)	CN	Q (mm)	T_p	T_c	Q_p	q_p	Wp50
Andhi jhora	4.87	3.07	372	76.39	699.08	355.73	67.48	241.85	3.48	4.40	45.49	0.60	3.57
Balasan	30.89	17.09	2339	75.72	577.45	320.07	85.85	274.78	17.96	18.12	637.30	0.11	22.92
Chaiti	13.52	5.91	185	13.68	633.10	357.16	78.29	284.65	7.53	18.61	82.66	0.27	8.55
Chel	31.76	19.69	2310	72.73	677.60	370.49	80.25	304.77	19.41	18.80	279.11	0.10	25.03
Chhombo Chhu	76.91	31.78	4416	57.42	394.93	255.34	91.70	229.69	36.37	40.51	835.20	0.05	50.98
Choklong Khola	7.00	4.39	560	80.00	696.01	357.56	74.41	270.60	4.85	5.70	69.30	0.42	5.19
Churanthi	12.10	6.38	1013	83.72	701.09	360.86	81.61	300.23	7.41	8.51	68.94	0.27	8.40
Demka Jhora	7.87	3.38	119	15.12	613.98	350.76	80.11	285.00	4.54	11.84	72.23	0.45	4.82
Diana Chamurchi	32.00	16.29	3272	102.25	732.52	407.54	84.09	355.05	17.85	16.58	606.68	0.11	22.76
Dik Chhu	36.66	18.27	4656	127.00	491.88	297.82	81.43	238.07	20.04	16.93	552.81	0.09	25.94
Ghatia	23.60	11.00	2346	99.41	705.65	390.55	76.75	311.30	12.95	13.28	154.35	0.15	15.82
Ghatia sub	9.36	4.82	344	36.75	701.35	384.16	80.48	318.99	5.78	9.60	63.27	0.35	6.35
Ghish	40.32	17.55	2199	54.54	689.82	365.89	79.56	297.79	20.55	25.21	311.36	0.09	26.70
Ghoramara Khola	5.17	2.79	635	122.82	698.96	357.69	56.41	196.99	3.42	3.83	64.22	0.61	3.50
Gulma Khola	7.42	4.18	723	97.44	697.90	356.98	65.91	236.69	4.87	5.52	116.63	0.42	5.22
Gurujong Khola	7.86	4.27	138	17.56	637.72	359.49	80.87	296.26	5.04	11.17	44.40	0.41	5.44
Jaldhaka	66.41	30.85	4422	66.59	681.80	376.13	83.06	320.40	33.54	34.20	985.39	0.05	46.50
Kalej Khola	30.81	14.91	3363	109.15	395.53	238.43	74.47	158.55	16.84	15.71	560.54	0.11	21.31
Kali Khola	10.31	5.64	366	35.50	709.53	396.33	80.90	332.46	6.50	10.48	102.35	0.31	7.25
Kaligaiti	4.37	1.86	581	132.95	698.73	358.99	68.05	247.19	2.62	3.27	133.76	0.81	2.59
Kuji Diana	20.68	11.41	1709	82.64	707.65	393.84	75.67	310.34	12.39	12.89	197.76	0.16	15.05
Kumlai	10.26	4.54	180	17.54	628.30	355.89	78.49	284.13	5.87	13.69	81.86	0.35	6.45
Kurti	16.14	6.12	549	34.01	647.57	365.53	80.52	300.90	8.30	15.01	132.31	0.24	9.55
Kurti Nadi	9.81	4.35	305	31.09	700.52	381.15	81.15	318.48	5.64	10.62	66.63	0.36	6.17
Lish	19.44	10.72	1722	88.58	711.28	368.35	75.39	284.69	11.70	11.97	212.40	0.17	14.10
Mahananda	20.43	11.65	2073	101.47	651.66	349.83	81.78	290.03	12.44	11.80	330.07	0.16	15.12
Mal	18.24	9.48	1302	71.38	668.18	371.21	72.63	276.80	10.74	12.39	176.50	0.18	12.80
Mid Teesta Basin	101.92	25.89	3707	36.37	546.71	310.29	81.44	250.23	37.68	59.90	1101.39	0.05	53.06
Murti	32.05	15.52	2370	73.95	669.10	372.13	79.60	304.00	17.47	18.81	263.30	0.11	22.21
Neora	38.24	19.81	3003	78.53	676.65	373.01	81.62	312.18	21.21	21.04	263.52	0.09	27.67
Nidim Jhora	7.88	3.59	120	15.23	627.37	355.74	81.73	295.64	4.67	11.82	35.79	0.44	4.98
Prek Chhu	28.56	12.70	5131	179.66	389.05	246.50	91.84	221.35	15.11	12.24	955.05	0.13	18.84
Rakti Khola	12.74	6.16	1704	133.75	656.58	355.20	84.76	305.73	7.46	7.39	112.76	0.27	8.47
Raman Khola	45.64	24.44	3369	73.82	440.46	255.79	82.93	202.23	25.34	24.67	666.18	0.07	33.85
Rambi Khola	36.47	21.30	2763	75.76	515.01	291.30	87.39	251.49	21.46	20.57	329.62	0.09	28.03
Ramthi	15.26	7.42	1195	78.31	704.70	360.80	78.82	290.11	8.84	10.43	143.78	0.22	10.26
Rangit Khola	60.81	34.06	3027	49.78	460.02	271.13	76.21	194.78	33.70	35.76	516.15	0.05	46.76
Rangyong Chhu	57.16	25.89	7697	134.66	389.40	252.65	89.00	218.52	28.87	23.25	1255.04	0.06	39.24
Rani Khola Chhu	38.54	19.99	4348	112.82	565.24	317.88	78.14	246.10	21.37	18.41	532.96	0.09	27.91
Rathang Rimbi Khola	42.51	19.90	3985	93.74	392.27	242.90	77.48	172.37	22.31	21.31	553.82	0.08	29.30
Reli Khola	36.34	16.11	2190	60.26	697.66	367.90	86.25	323.39	18.83	22.41	410.02	0.10	24.18
Relli Chhu	32.51	16.60	4889	150.38	397.48	254.94	82.95	201.49	18.14	14.47	769.99	0.10	23.18
Rohini Khola	12.35	6.95	1665	134.82	662.41	358.35	84.80	308.96	7.78	7.20	125.50	0.26	8.88
Rong dong	6.98	5.09	588	84.24	698.82	362.15	80.85	298.78	5.18	5.57	131.81	0.39	5.60
Rongpo Rangli Khola	57.14	26.09	4434	77.60	627.19	348.50	82.73	292.06	28.97	28.74	868.13	0.06	39.39
Rongsung Khola	5.64	3.08	843	149.47	675.91	362.45	87.99	323.92	3.73	3.80	103.54	0.56	3.86
Rongtong Khola	7.14	4.03	496	69.47	671.09	361.21	69.64	255.58	4.70	6.11	135.87	0.44	5.02
Shevok Khola	7.90	3.62	1025	129.75	677.76	362.71	82.28	304.44	4.69	5.19	180.74	0.44	5.00
Sukhani Jhora	9.68	5.09	254	26.24	700.99	382.29	80.44	316.99	6.02	11.22	64.10	0.34	6.65
Sukna Jhora	8.31	4.43	651	78.34	670.06	361.36	72.27	266.01	5.27	6.55	75.09	0.39	5.71

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Table 6 (continued)

Watershed	L	L_c	H	S	AmR (mm)	ER (mm)	CN	Q (mm)	T_p	T_c	Q_p	q_p	Wp50
SuknaJhora Sub	6.49	3.45	379	58.40	674.75	362.73	69.44	256.23	4.19	6.07	54.50	0.50	4.40
Teest Upper	52.92	25.89	4831	91.29	439.75	275.74	85.00	228.41	27.86	25.46	1224.86	0.07	37.69
Teesta sub	2.84	1.40	659	232.04	683.97	366.38	79.78	299.07	1.89	1.90	46.24	1.15	1.79
Teesta Sub 1	13.68	8.07	1905	139.25	535.15	299.31	87.45	259.62	8.73	7.69	133.69	0.23	10.13
Teesta Sub 2	19.20	10.35	2307	120.16	554.71	308.38	85.14	260.90	11.45	10.54	269.94	0.17	13.76
Yumthang Chhu	41.09	20.00	4143	100.83	417.25	266.26	94.04	247.87	22.02	20.19	1149.66	0.08	28.87
Zemu Chhu	58.67	31.78	5906	100.66	382.60	247.97	94.80	231.99	32.11	26.53	1357.50	0.06	44.26

so frequent but these are larger in magnitude. These rivers directly fall into the piedmont; hence these cause much devastation during a storm event. Most of the sub-basins of the Teesta have a very high time to peak, time of concentration and W_{50}, thus these watersheds are less susceptible to flash flood.

Hydrological response and flash flood susceptibility

The basin-wise flash flood susceptibility was estimated based on the relationship of run-off depth (Q) and parameters of unit hydrograph with flash flood. The compound value (Table 7) calculated from averaging the rank was used for flash flood susceptibility (Roughani et al. 2007; Prasad and Pani 2017). The result (Fig. 6) shows that Teesta Sub 2, Mahananda, Teesta Sub1, Lish, Ghatia, Kumlai, Kurti, Sukna Jhora, Kuji Diana, Ramthi, Reli Khola, Gulma Khola, Gurujong Khola, SuknaJhora Sub, Choklong Khola, Rohini Khola, Rongtong Khola, Rakti Khola, Ghoramara Khola, Churanthi, Andhi jhora, Diana–Chamurchi, Sukhani Jhora, Demka Jhora, Nidim Jhora, Ghatia sub, Kurti Nadi, Rong dong, Kali Khola, Kaligaiti, Teesta sub, Shevok Khola and Rongsung Khola falls in very high susceptibility class. Whereas Rangit Khola, Rathang Rimbi Khola, Mid Teesta Basin and Chhombo Chhu falls under low susceptibility (Fig. 6).

In summary, the analysis of rainfall–runoff model and unit hydrograph parameters reveals that the smaller drainage basins are more susceptible to flash flood due to their short time of concentration (T_c), short time to peak (T_p) and W_{50}. There is no doubt that the frequency of flash flood in these basins is very high, but the field investigation and available records show that the magnitude of flash floods is not so significant to cost any damage to infrastructure due to very small areal coverage, but still these pose a significant risk for human lives and properties. Most of the larger basins in this region are capable of producing larger magnitude flash floods. Hence these watersheds produce significant risk to railway and highway bridges, culverts, settlements as well as to human lives and society.

Flash flood risk

To come up with the final flash flood risk map, we integrated both the susceptibility maps. Higher weight was assigned to the susceptibility map estimated from rainfall–runoff modelling and parameters of the synthetic unit hydrograph. To determine the weight, we consulted the engineers, scientist and geomorphologists. The resulted flash flood risk map indicates that Shevok Khola, Teesta sub, Kaligaiti. Rong dong, Ghoramara Khola, Rongsung Khola, Andhijhora, Gulma Khola, Diana–Chamurchi, Ramthi, Lish, and Churanthi khola are the most risky basins of the study area. Relli Chhu, Prek Chhu, Rongtong Khola, Choklong Khola, Teesta Sub 2, Kuji Diana, Balasan, Mahananda, Dik Chhu, Rohini Khola, SuknaJhora Sub, Rakti Khola, Mal, Rambi Khola, Raman Khola, Jaldhaka, Ghatia, Neora, Reli Khola, Teest Upper, Suknajhora, Chel and Ghish basins are fall in the high-risk category. The flash flood inventory (Fig. 7) and the relatively high damage sites in the piedmont region of Jalpaiguri District, which mostly include the damages to the transport network (Fig. 8), were found mostly in the very high and high flash flood risk watersheds. Almost all the rivers of Jalpaiguri District suffering from channel aggradation and consequent river bed raising due to the excessive amount of debris brought and deposited by the flash floods. In addition to this, the settlements, tea gardens, and agricultural fields situated close to these rivers are many times affected by the flash floods. More or less every year, few people are reported to be swept away by the flash floods in some of the rivers. Jalpaiguri District is endowed with many rivers, ranging from jhoras (small streams) to rivers. And in remote areas there are no bridges to cross these rivers, so people have no way but to cross the rivers even during the monsoon months when the rivers are in their surge. Many time during flash floods, these rivers change their course and affect the settlements, tea gardens and agricultural land which come their way. The rest of the watersheds fall in moderate and low categories.

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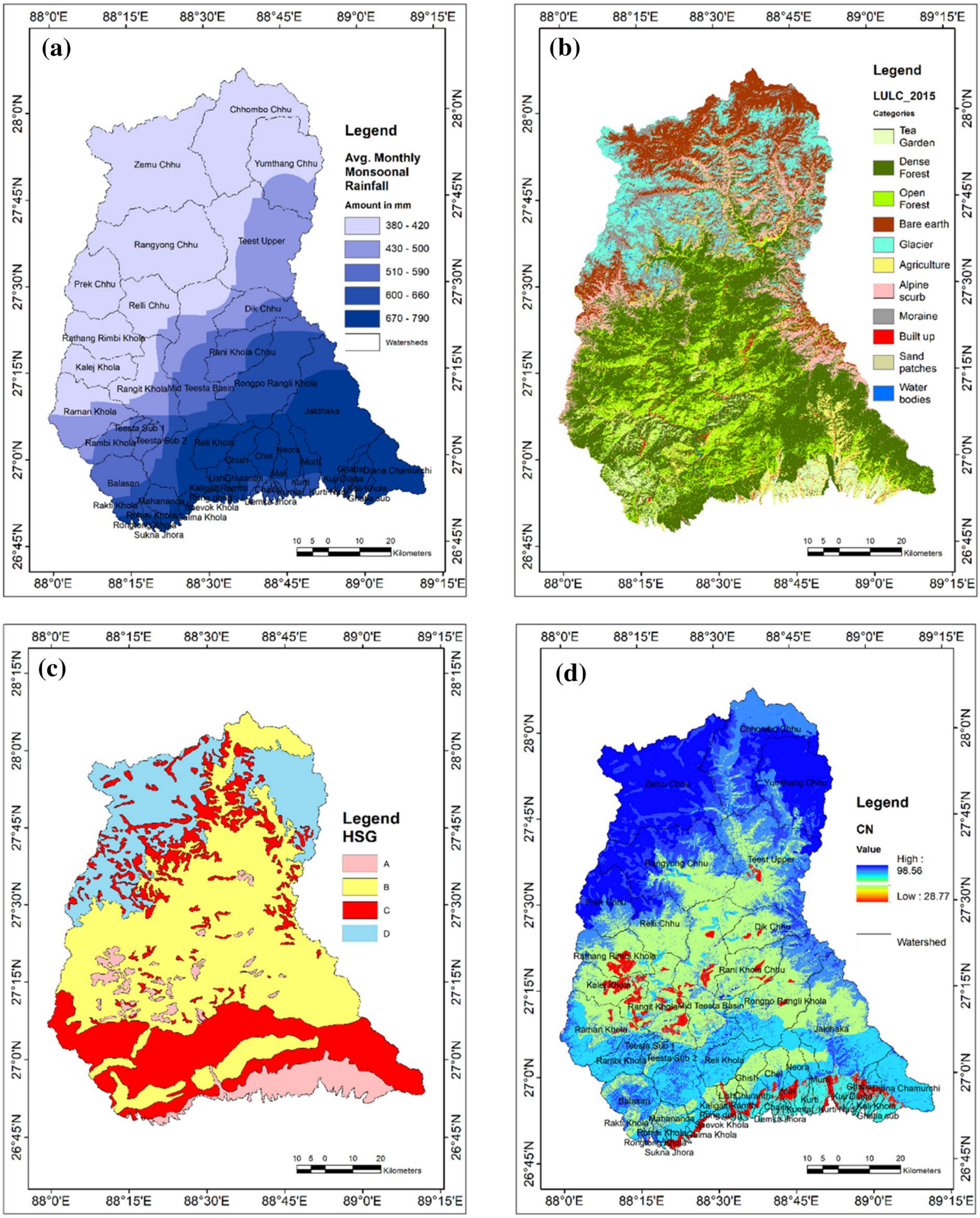

Fig. 5 **a** Average monthly monsoonal (May–September) rainfall, **b** land use and land cover, **c** hydrological soil group, **d** curve number, **e** event rainfall of 13th August 2017, **f** run-off depth estimated from event rainfall of 13th August 2017, **g** time to peak, **h** time of concentration

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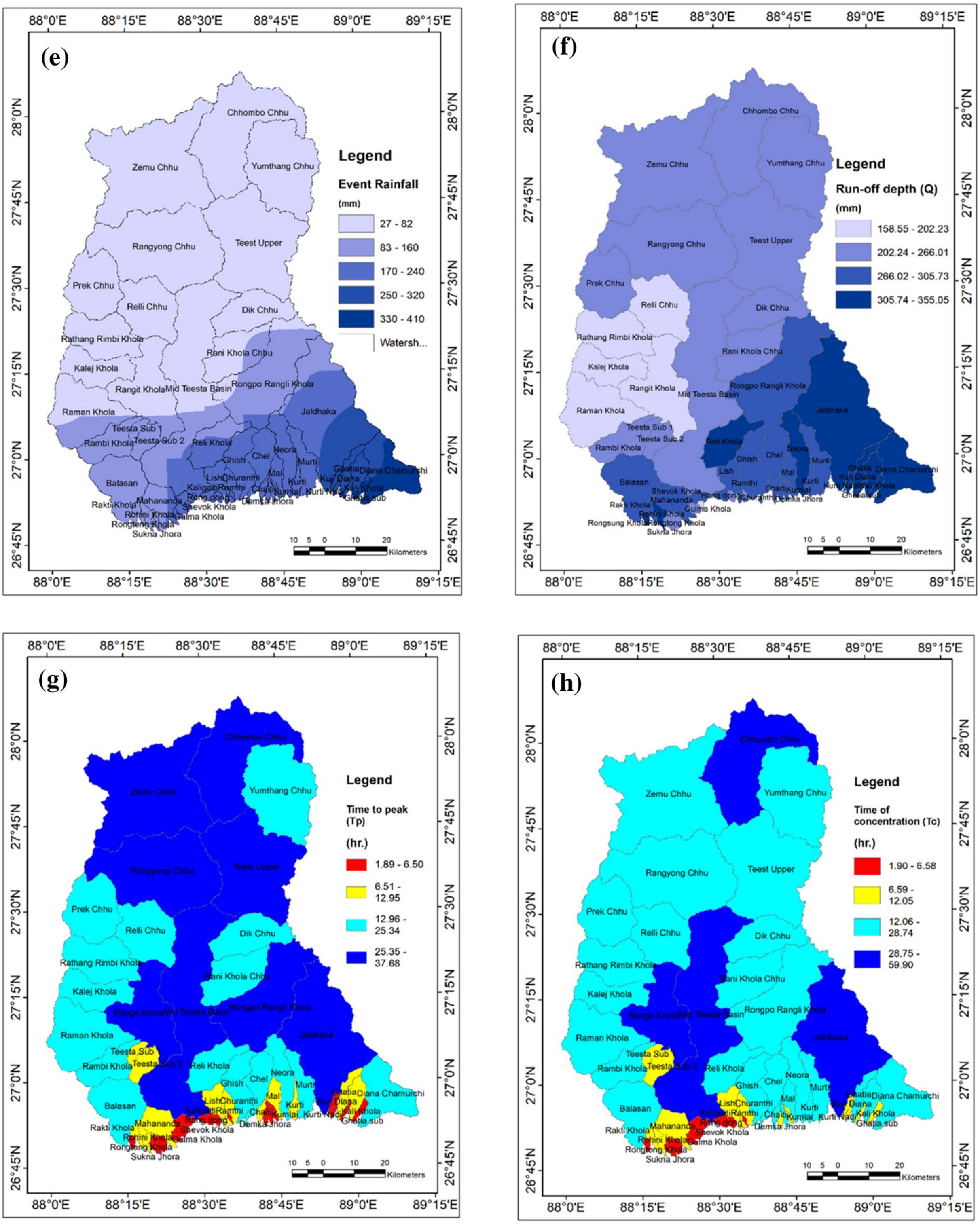

Fig. 5 (continued)

Conclusion

The present study gives us a basic idea about the morphometric characteristics and hydrologic behaviour of the watershed of Himalayan foreland of Jalpaiguri and Darjeeling Districts and some causes behind the high susceptibility to flash flood. We assessed the flash flood susceptibility with a holistic approach considering the morphometry,

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Table 7 Primary ranking of watersheds based on hydrologic parameters and calculated C_p

Watershed	CN	AmR	Q	T_p	T_c	Q_p	q_p	W_{50}	C_p
Andhi jhora	3	47	14	54	54	3	54	54	35.375
Balasan	48	18	26	20	20	46	20	20	27.25
Chaiti	17	23	29	35	35	15	35	35	28
Chel	24	36	44	17	17	35	17	17	25.875
Chhombo Chhu	54	5	10	2	2	49	2	2	15.75
Choklong Khola	9	41	25	47	47	11	47	47	34.25
Churanthi	34	50	40	37	37	10	37	37	35.25
Demka Jhora	23	19	31	51	51	12	51	51	36.125
Diana Chamurchi	43	57	57	21	21	45	21	21	35.75
Dik Chhu	32	12	13	16	16	42	16	16	20.375
Ghatia	14	53	48	25	25	27	25	25	30.25
Ghatia sub	26	51	52	41	41	6	41	41	37.375
Ghish	20	40	37	15	15	36	15	15	24.125
Ghoramara Khola	1	46	4	55	55	8	55	55	34.875
Gulma Khola	2	43	12	46	46	19	46	46	32.5
Gurujong Khola	29	24	36	45	45	2	45	45	33.875
Jaldhaka	42	38	53	4	4	52	4	4	25.125
Kalej Khola	10	6	1	23	23	44	23	23	19.125
Kali Khola	30	55	56	38	38	16	38	38	38.625
Kaligaiti	4	44	16	56	56	24	56	56	39
Kuji Diana	12	54	47	27	27	30	27	27	31.375
Kumlai	18	22	28	40	40	14	40	40	30.25
Kurti	27	25	41	33	33	22	33	33	30.875
Kurti Nadi	31	48	51	42	42	9	42	42	38.375
Lish	11	56	30	28	28	31	28	28	30
Mahananda	37	26	32	26	26	38	26	26	29.625
Mal	8	29	27	30	30	28	30	30	26.5
Mid Teesta Basin	33	15	18	1	1	53	1	1	15.375
Murti	21	30	42	22	22	32	22	22	26.625
Neora	35	35	49	14	14	33	14	14	26
Nidim Jhora	36	21	35	50	50	1	50	50	36.625
Prek Chhu	55	2	8	24	24	51	24	24	26.5
Rakti Khola	44	27	45	36	36	18	36	36	34.75
Raman Khola	40	10	6	9	9	47	9	9	17.375
Rambi Khola	50	13	19	12	12	37	12	12	20.875
Ramthi	19	52	33	31	31	26	31	31	31.75
Rangit Khola	13	11	3	3	3	40	3	3	9.875
Rangyong Chhu	53	3	7	7	7	56	7	7	18.375
Rani Khola Chhu	16	17	15	13	13	41	13	13	17.625
Rathang Rimbi Khola	15	4	2	10	10	43	10	10	13
Reli Khola	49	42	54	18	18	39	18	18	32
Relli Chhu	41	7	5	19	19	48	19	19	22.125
Rohini Khola	45	28	46	34	34	20	34	34	34.375
Rong dong	28	45	38	44	44	21	44	44	38.5
Rongpo Rangli Khola	39	20	34	6	6	50	6	6	20.875
Rongsung Khola	52	34	55	53	53	17	53	53	46.25
Rongtong Khola	6	32	20	48	48	25	48	48	34.375
Shevok Khola	38	37	43	49	49	29	49	49	42.875
Sukhani Jhora	25	49	50	39	39	7	39	39	35.875
Sukna Jhora	7	31	24	43	43	13	43	43	30.875
SuknaJhora Sub	5	33	21	52	52	5	52	52	34

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Table 7 (continued)

Watershed	CN	AmR	Q	T_p	T_c	Q_p	q_p	W_{50}	C_p
Teest Upper	46	9	9	8	8	55	8	8	18.875
Teesta sub	22	39	39	57	57	4	57	57	41.5
Teesta Sub 1	51	14	22	32	32	23	32	32	29.75
Teesta Sub 2	47	16	23	29	29	34	29	29	29.5
Yumthang Chhu	56	8	17	11	11	54	11	11	22.375
Zemu Chhu	57	1	11	5	5	57	5	5	18.25

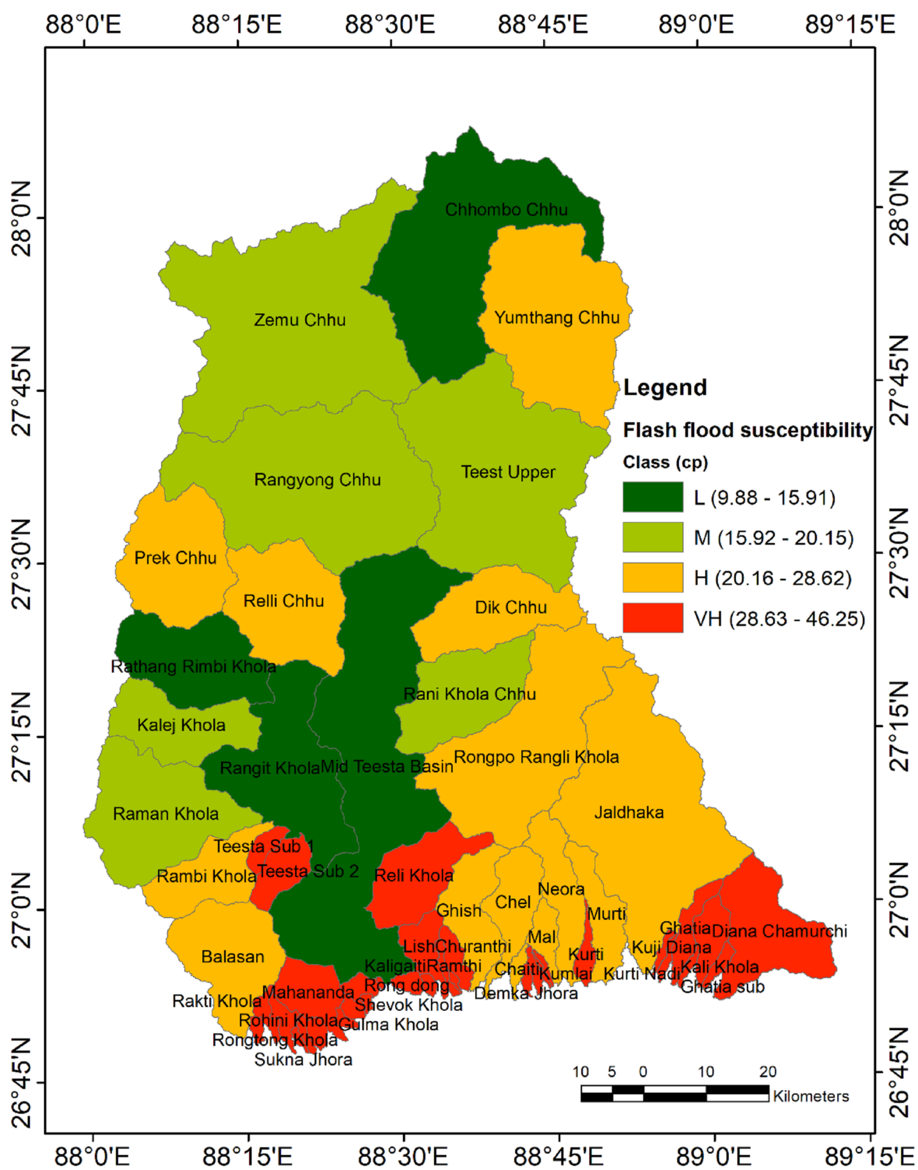

Fig. 6 Flash flood susceptibility map based on the compound value of rainfall–run-off and parameters of the synthetic unit hydrograph

hydrology, land use land cover, geology, soil and climatic characteristics of the watersheds. We used GIS to extract various information from remote sensing data and conducted field studies to verify the results.

Morphometric characteristics of the watersheds govern the hydrological response of the watersheds and hence enable us to infer the susceptibility to flash flood. A morphometric analysis of the catchments reflects the general cause behind the high susceptibility to flash flood. Based on the compound value of morphometric ranks, the flash flood susceptibility map of the watersheds of Himalayan foreland of Jalpaiguri and Darjeeling Districts could be classified into

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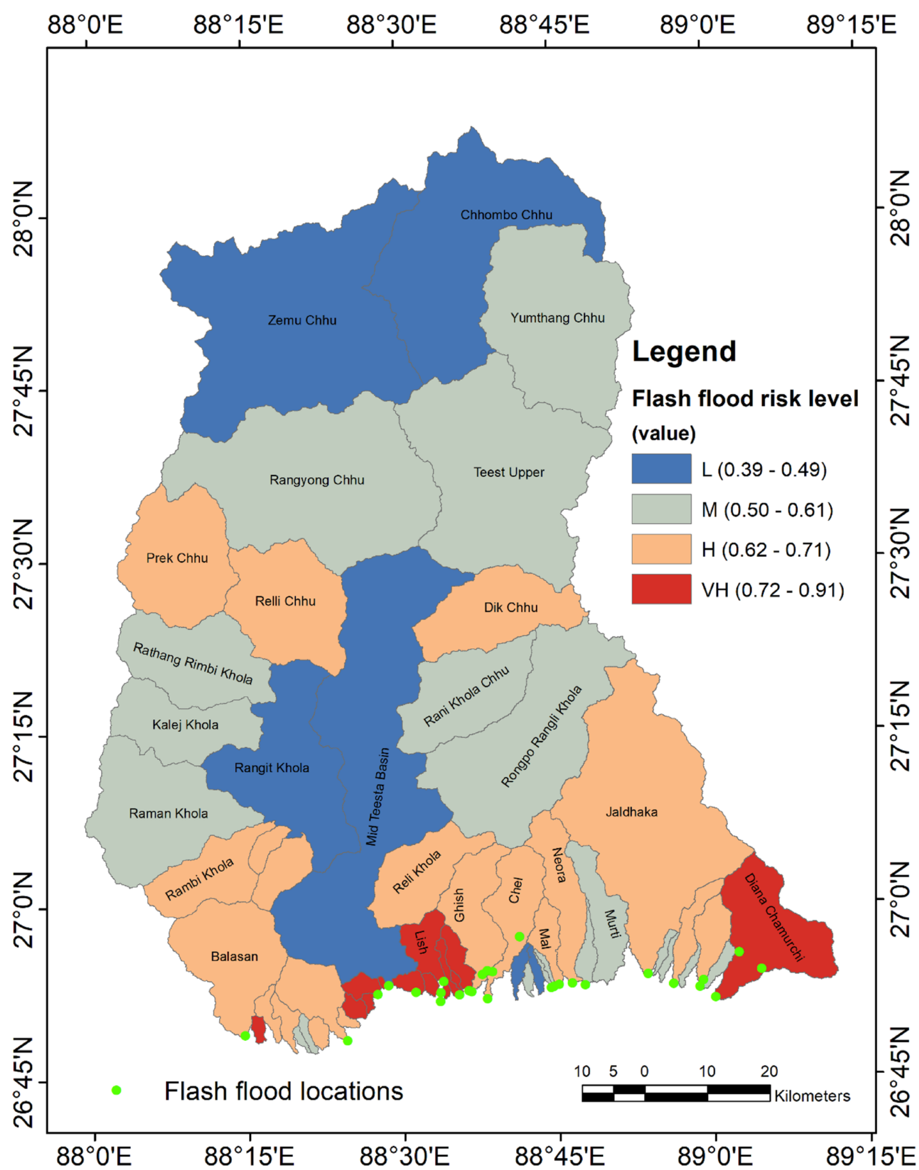

Fig. 7 Flash flood risk map shows the different level of risk watersheds and locations affected by the flash flood in the piedmont of Jalpaiguri and Darjeeling Districts

groups: 1. very highly susceptible, 2. highly susceptible, 3. moderately susceptible, and 4. low susceptible to flash flood. Morphometrically high to very highly susceptible basins is characterized with medium to high drainage density, stream frequency, texture ratio, drainage intensity and very high relief, relief ratio and average slope. All these characteristics reflect the potentiality of high run-off generation and quick discharge and thus high possibility of a flood.

Run-off modelling and synthetic unit hydrograph are two methods that provide the opportunity to estimate the hydrological response of watersheds for ungauged basins. The parameters of run-off modelling and unit hydrograph reflect the hydrological characteristics to consider the susceptibility of the basins. In the present study, we found that the smaller to medium basins of piedmont and foothills region are highly susceptible to flash flood in terms of frequency because of their very short time to peak (T_p) and time of concentration and less W_{50}. On the other hand, the larger basins of Higher and Lesser Himalayas are susceptible to high magnitude flash flood due to their very high peak flow rate (Q_p).

The flash flood risk map indicates that the railway line and highway in the piedmont region of Jalpaiguri and Darjeeling Districts at the locations of their intersection with Shevok Khola, Teesta, Ramthi Chel, Neora, Mal, Jaldhaka, Ghatia and Diana, and settlements near these locations are the most susceptible to be damaged due to flash floods. Signature of the past destruction also confirms this result. The railway and highway bridges at these locations were destroyed in the 1968 flash flood (Fig. 8a–d). The railway bridge of Ghish river was destroyed by the flash flood in 2008. During the

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Fig. 8 Some signatures of destruction by the flash flood: Along with almost all the rivers of Jalpaiguri District. **a** Chel, **b** Diana–Chamurchi, **c** Ghatia, **d** Lish river bridges were destroyed in the flash flood of 1968, **e** more than 1 m sediment was removed by the flash flood in Ramthi river in 2011, **f** flash flood in Ramthi river, 2019, **g** bailey bridge in Samtse, Bhutan collapsed in July 2016 due to flash flood in Diana–Chamurchi river (http://www.bbs.bt/news/?p=60607). **j** In Ghish river, channel bed raised to the height of the embankment. Roads were washed away by the flash floods in the **h** Ghaita river and Kurti river in 2019. **k** An excessive amount of sediment brought down by the flash flood during the last 38 years raised the bed of Lish river more than 3 m

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last 10 years, the flash flood is most frequent in Ramthi river. During a flash flood in 2011, the Ramthi river changed its course. More than 1-m-thick sediment layer was removed near Uttar Fulbari, from where Ramthi river changed its course (Fig. 8e). In 2018, two persons were drowned by the flash flood in Ramthi river near Ghish Basti. Recently, during the monsoon of 2019, the railway underpass on Ramthi river was damaged by a flash flood. River Diana–Chamurchi is one of the most highly flash flood-prone rivers in the study area. It damages the bridge in the Bhutanese piedmont more or less every year (Fig. 8g). Settlements and roads in many places in Nagrakata block of Jalpaiguri District were damaged due to flash flood in the tributaries of Jaldhaka river (Fig. 8h, i) during the last monsoon. One person is swept away by Diana river in Angrabhasa of Nagrakata.

Field investigation since 2012 revealed that settlements are gradually developing into the floodplain of some of the highly flash flood-prone rivers, like Rong Dong, Ghish, Chel, Ghatia and Diana. The government should take necessary steps to reduce the impact of the flash floods in this highly susceptible watersheds. However, at these intersection points, the rivers were narrowed down to construct the bridges which accelerated the deposition and result in channel bed level raising that further culminated the problem (Fig. 8j, k). From our findings, it is recommended to reconsider the channel confinement to avoid damages. Authorities should also take proper steps to restrict the development of settlements in these high hazards prone zones.

In the present study, the topography, climate, soil, land use and land cover and morphometric characteristics are evaluated to assess the susceptibility to flash flood. The morphometric analysis, run-off modelling and parameters of unit hydrograph were integrated to access the flash flood susceptibility of the watersheds and verified by intensive field investigation and available records. The estimated result of flash flood risk assessment and the field diagnosis and the available records of past flash floods are quite an in agreement. The basins with the highest flash flood risk are aligned with observed and recorded flood events. This comparison provides an evaluation of the modelling performance and credibility of the model performance. As our study adopted a holistic approach and verified by field investigation, this study could form the basis for the planning of watershed management to reduce the severity of the flash flood hazards in the piedmont region of Jalpaiguri and Darjeeling Districts. Moreover, the methodology adopted for the study can be applied to other high mountainous regions.

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Authors' contribution The first author designed the framework of the research. The first author prepared the maps, analyzed the data and drafted this manuscript. The second author corrected the manuscript. The authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Availability of data and materials Geological maps were collected from the Geological Survey of India, Kolkata. Sentinel 2B satellite images were downloaded from SCI data hub (https://scihub.copernicus.eu/dhus/#/home), and Jaxa 30m DSMs are downloaded from Japan Aerospace Exploration Agency (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm). Landsat 8 OLI/TIRS images were downloaded from the USGS website. All data are processed in the Geography laboratory of Lady Brabourne College (University of Calcutta).

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