



Integrated framework for flood relief package (FRP) allocation in semiarid region: a case of Rel River flood, Gujarat, India

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Abstract

Flash flood is disastrous; it losses property and life. Its effect is intensified while it occurs in semiarid region because of less preparedness. The present case conferred about a flash flood in semiarid region in Gujarat which was affected by flood in 2015 and 2017. Massive loss of lives and properties has been observed after the event. Now, recuperating the region against flood losses, it was a prime requirement to distribute the flood relief packages to the flood-susceptible areas. To identify the flood hazards and flood risk and assess the flood vulnerability in Rel River catchment, the region is divided into 52 micro-watersheds using RS and GIS techniques. The morphology of the Rel River catchments has been explored using the morphometric analysis. The priority rank and category for each micro-watershed were assigned based on compound factor values, whereas compound factor was calculated using weighted sum analysis techniques. Flood hazard zone map was prepared, and flood vulnerability has been characterized from very low to very high. Furthermore, the multi-criteria analysis was used to calculate the risk factor for the basin and AHP-MCE method was used to find the normalized weights of each factor (LU/LC, CF, soil, slope, drainage density) that were significant to the flood disaster. The integration of flood hazard map along with these parameters helped to understand the sensitivity of flash floods at different locations within the study area. Flood risk map was further analyzed at village level, and it has been identified that 17 out of 39 villages were at high risk, 12 villages were at moderate risk and 10 villages were at low risk. The study helped to clearly identify villages vulnerable to flood risk where more relief and flood insurance packages need to be allotted. Thus, the present method and integrated approach would be a useful tool for the decision maker to distribute the flood relief package in flash flood-prone area.

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Keywords AHP · Flash flood · Flood hazard · Morphometric · RS · GIS

Abbreviations

AHP	Analytical hierarchy process
CR	Consistent ratio
DRIP	Dam Rehabilitation and Improvement Project
<i>e</i>	Eigen vector
EAP	Emergency action plan
FRP	Flood relief package
FHV	Flood hazards vulnerability
LU	Land use
LC	Land cover
Me	Eigen matrix
MCE	Multi-criteria evaluation
MWS	Microwater shed
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
<i>n</i>	Number of variables
PPR	Preliminary priority rank
RI	Random inconsistency
SAVI	Soil-adjusted vegetation index
SBI	Soil brightness index
SWAT	Soil and water assessment tool
WMP	Weight of morphometric parameter
λ_{\max}	Largest Eigen value

1 Introduction

Flash floods are among the catastrophic natural hazards in the world causing the largest amount of deaths and property damage (CEOS 2003; Jonkman and Vrijling 2008; Singh and Kumar 2018). Globally, about one-third of the land surface is vulnerable to floods, where more than 70% population is residing (Aksoy et al. 2016; Singh and Kumar 2018). India is the worst flood-affected country in the world after Bangladesh and accounts for one-fifth of the global death count due to floods (Agarwal and Narayan 1991). Flash flooding is one of the most severe hazards that damage infrastructure, threatening life and property. Flash floods are caused by excessive rainfall in the arid and semiarid area (Taha et al. 2017). Flood hazard mapping is a component needed for appropriate land use in the flooded area. Flood hazard mapping in arid regions is an extremely important but difficult task due to the scarcity of data (Bajabaa et al. 2014). It is relatively difficult and time-consuming to perform the flood hazard analysis for a large area from time to time. Remote sensing coupled with morphometric analysis and GIS tool provides a good platform to combine, manipulate and analyze the information for the determination of potential flood area very quickly and more efficiently (Youssef et al. 2011).

In order to estimate the flood response, it is very important to understand morphometric parameters like stream magnitude, drainage density and topography in flash flood-prone regions (Waikar and Nilawar 2014). For this purpose, remote sensing (RS) and geographical information system (GIS) technology has been used to find the interrelation of

morphometric parameters and further identify the area under varying flood conditions. One of the useful applications of GIS is toward watershed prioritization, which refers to the ranking of different mini-watersheds according to the order of development. By prioritization of watersheds, one can conclude which watershed can lead to a higher amount of discharge due to the excessive amount of rainfall and erosion (Chowdary et al. 2009; Edet et al. 1998; Javed et al. 2009, 2011). Several studies are cited in the literature, relating to flood hazard mapping and zonation using GIS (Bajabaa et al. 2014; Fernández and Lutz 2010; Guzzetti and Tonelli 2004; He et al. 2003; Merzi and Aktas 2000; Sanyal and Lu 2006; Sui and Maggio 1999). Morphometric studies were first initiated by R.E. Horton and A.E. Strahler in the 1940s and 1950s (Pidwirny 2008). Morphometric analysis is carried out through the measurement of linear, aerial and relief aspects of the basin. Many pioneers (Bhatt and Ahmed 2014; Choudhari et al. 2018; Horton 1945; Kumar et al. 2000; Patel et al. 2015; Schumm 1956; Smith 1950; Verstappen 1983) have studied and developed various morphometric parameters such as stream order, basin area and perimeter, stream length, basin length, drainage density (D_d), stream frequency (F_s), bifurcation ratio (R_b), texture ratio (T), relief ratio (R_h), time of concentration (T_c) and infiltration number (I_p) to analyze the behavior of surface drainage networks and characteristics of the basin. These parameters have been utilized to prioritize the watersheds to study the flood characteristics (Alexander 1972; Angillieri 2008; Chopra et al. 2005; Javed et al. 2009; Patel et al. 2012; Roughani et al. 2007). Yadav et al. (2014) applied morphometric analysis of Upper Tons basin of Northern Foreland of Peninsular, India, to explore the interrelationship between hydraulic and geomorphological parameters for disaster prevention. (Kumar et al. 2018a) studied an integrated approach (spectral indices, i.e., NDVI, SAVI, NDWI, SBI and morphometry) for a part of Yamuna and Ken River basin, India, and concluded that the morphometric parameters are highly influenced by hydraulic activities and signify important role in the fluvial morphometric process. (Chowdary et al. 2013) have conducted a study for prioritization of micro-watersheds using multi-criteria decision approach of AHP and sediment yield index model (AHP SYI) under GIS environment. (Patel et al. 2015) have proposed AHP-MCE approach to identify a suitable site for water harvesting structure in addition to the morphometric analysis, whereas (Kumar Pradhan et al. 2018) provided a new approach to identify the soil erosion-susceptible zones using RUSLE, morphometric analysis and AHP-MCE techniques. Sinha et al. (2008) proposed a flood risk index (FRI) for flood risk analysis using analytical hierarchy process (AHP) and integrated geomorphological, land cover, topographical and social (population density) parameters for a part of Kosi River basin. Chen et al. (2011) concluded that integration of AHP and GIS in flood risk assessment can provide useful detailed information for flood risk management. (Syed et al. 2017) have used multi-criteria analysis to calculate risk factor and prepared flood risk map with a very low, low, medium, high, very high category. (Malik et al. 2019) utilized weighted sum analysis (WSA) approach for prioritization of 14 hilly sub-watersheds of upper Ramganga River basin, Uttarakhand State, India. Many researchers used pairwise comparison, within analytic hierarchy process method (AHP) and geographical information system (GIS), to assess flood hazard (Chen et al. 2011; Emmanouloudis et al. 2008; Meyer et al. 2009; Singh and Kumar 2018; Stefanidis and Stathis 2013). (Franci et al. 2016) confirmed the benefits of using remote sensing data coupled with MCA approach to provide fast and cost-effective information concerning the hazard assessment, especially when reliable data are not available.

The present study describes the case of a flash flood in semiarid region which scares with data and watershed characteristics for evaluation of flood vulnerability. Rel River catchment, situated at Banaskantha District, was a case which was affected by flood in

2015 and 2017. To fill the research and data gap as well to identify the basin morphology and understand the role of different morphology parameters, the work is employed over the 52 micro-watersheds. The ArcGIS and ArcHydro tool has been used to derive a basic parameter for morphometric analysis, whereas correction matrix and weighted sum analysis (WSA) have been performed for compound factor and ranking. Priority (very low, low, moderate, high and very high) has been fixed based on the compound factor. This priority rank and integrated priority rank maps helped to understand the sensitivity of flash floods in different micro-watersheds of the study area. Morphometric analysis along with high-resolution satellite technology and GIS combined provides a strong base to explore the flood hazard potentiality of micro-watersheds. AHP-MCE helps to find the weightage of all the parameters. Weighted risk mapping is an important technique used in this study, to prioritize a micro-watershed based on the risk factor. Furthermore, a risk map is overlaid on the village map and identified vulnerable villages where more relief activity is required. A first unique concept has been formulated to allocate a flood relief package allocation in flood-vulnerable areas in India. The concept is not limited to flood, but it can be applicable to prioritize any disaster vulnerable area using RS, GIS, weight overlay analysis and AHP-MCE method.

2 Study area and agro-climatic description

2.1 Rel River morphology and flood 2017

Rel River (Sukal Nadi) basin originates from Keshua Village, Aravalli Hills of Rajasthan State, and flows in Gujarat. The Rel River basin is the northern basin and lies between $24^{\circ} 50' N$ to $24^{\circ} 75' N$ latitude and $72^{\circ} 00' E$ to $72^{\circ} 45' E$ longitude and covers an area of approx 442 km^2 (Fig. 1). The basin is bounded both in the east and west by prominent hills of Aravalli range. The hills on the western side are higher and are part of Mt. Abu range. The streams originating from hills flow in NE–SW directions and drain into little Rann of Kutch. Being part of the Mt. Abu range, the maximum elevation seen within the basin is about 609 m., while the general elevation within hilly part is in the 250–750 m range. The overall slope of the terrain is northeast to southwest direction. The lowest point is near Dhanera Taluka and Dhanera City itself, and it is located near the exit point of the basin at southwest of Abu road, Banaskantha District. Further, Rel River basin and its watersheds are divided into 52 micro-watersheds, with an average area of 7 km^2 . Entire study area falls within the toposheet numbered 45 D/02, 03, 06 at the scale of 1:50,000. It is considered a hot semiarid region in western India and experiences hot summer from March to mid-June. The maximum dry temperature ranges between 42 and 45 °C. The region encompasses three distinct seasons: winter, summer and monsoon. The temperature increases from January onwards having maximum values during May and gradually decreases afterward. With the onset of monsoon, southwest winds are strong and humid, with relative humidity more than 50%. The region is predominately inhabited by the tribal population, which till a few decades ago is mainly depended on forests for its livelihood and now also practices subsistence agriculture for food and fodder.

Rel River is having very steep topography in the upper catchment with a maximum elevation of 609 m and reduces to 77 m in the plain area near Dhanera Tehsil; such a large variation in elevation of river catchments leads to a flash flood in catchment. Recently, Rel River catchment has recorded an average rainfall of 257 mm on 24–25th 2017. It was

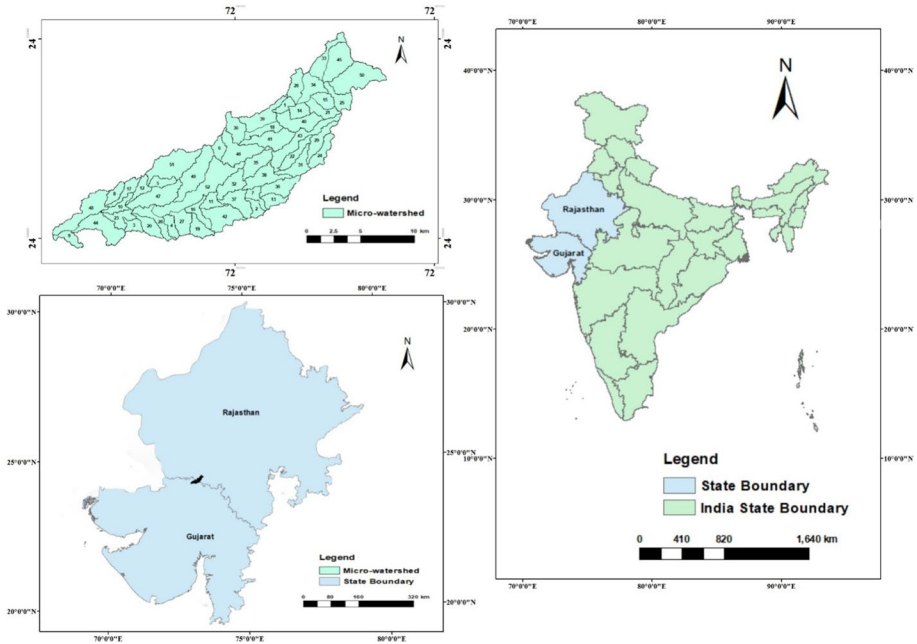


Fig. 1 Location map of Rel River micro-watersheds

close to the heaviest rainfall in 112 years in this region, resulted very heavy runoff in the catchment of Rel River. Due the lack of the discharge carrying capacity of the river and heavy rain on catchment, Dhanera area and Dhanera City were flooded more than 30 h and observed under an inundation of 2.5–3 m in water (Fig. 2). Near about 72 people died,



Fig. 2 a, b Photographs show the Rel River flood 2017; c, d photographs show the Dhanera City inundate in the flood 2017

81,609 cattle killed, and property damaged worth INR 2000 crore was in Banaskantha, Patan and Kutch districts. Dhanera was the highest flood-affected city among the other of Banaskantha District. Entire stretch of Banaskantha District was under catastrophic flood, and very heavy damages were reported. The Government of India announced an interim flood relief package of INR 500 crore as initial assistance. The state government demands INR 4700 crore as compensation for damages. Around INR 1700 crore is the estimated loss for agricultural production and agricultural land, while INR 700 crore is for damage to state highway and village roads. Public infrastructure facilities like schools, colleges, hospitals demanded more than INR 1000 crore. To restore public amenities and other private properties, it is at most important to distribute the flood relief package as per the flood hazards in this area; however, due to lack of the information of basin geomorphology, hazard and flood risk area, the FRP allocation process is slowed down, hampering the restoration process in this region.

3 Material and methodology

As shown in the methodology flowchart in (Fig. 3), IRS P6 (LISS-III) sensor data was used as a primary source, and unsupervised classification was performed in ERDAS imagine 2015 (Table 1). This was incorporated into GIS environment to prepare final land use/land cover map of the study area. NBSS & LUP soil data, SOI toposheets at 1:50,000 scale and CartoDEM with 30 m spatial resolution were used as secondary sources. The data sources along with their specifications are provided in Tables 1 and 2. Slope, drainage and the watershed boundary were delineated from CartoDEM; the boundary was corrected using the SOI toposheets which were scanned and geo-rectified in ArcGIS 10.3. All the secondary data except soil layers were used to conduct morphometric analysis; this will be discussed later in the paper. Based on the morphometry of the basin, compound factor was calculated which was used to give ranks and prioritize the micro-watersheds. A compound factor was calculated using weighted sum analysis (WSA) techniques. Flood hazard zone map was prepared, and flood vulnerability has been characterized, i.e., very high, high, moderate, low and very low category. The flood hazard map so obtained was further combined with the LU/LC, CF, soil, slope, drainage density, and weighted risk map was prepared using AHP-MCE method. These weighted maps were used to prepare flash flood risk map of the whole study area, and village boundary of only those villages that fall under Gujarat region of Banaskantha District was overlaid, and flood-assessed villages along with the risk vulnerability of each village were analyzed. The preceding sections give the details on procedure and analysis of each parameter used for flash flood risk mapping and also the assessment of the flood risk map at village level which was performed for flood relief package allocation.

3.1 Drainage network

Drainage can be defined as the entire geographical area drained by a river and its tributaries, found to be an important parameter for flood control in most of the basins. The topographical maps were then scanned with 400 dpi resolution. Scanned map was georeferenced in Arc GIS 10.3 software and then converted into UTM WGS 1984 42 NProjection system. The shape file for drainages was digitized from the registered topographical sheets. Human errors produced during digitization process such as overshoot/undershoot,

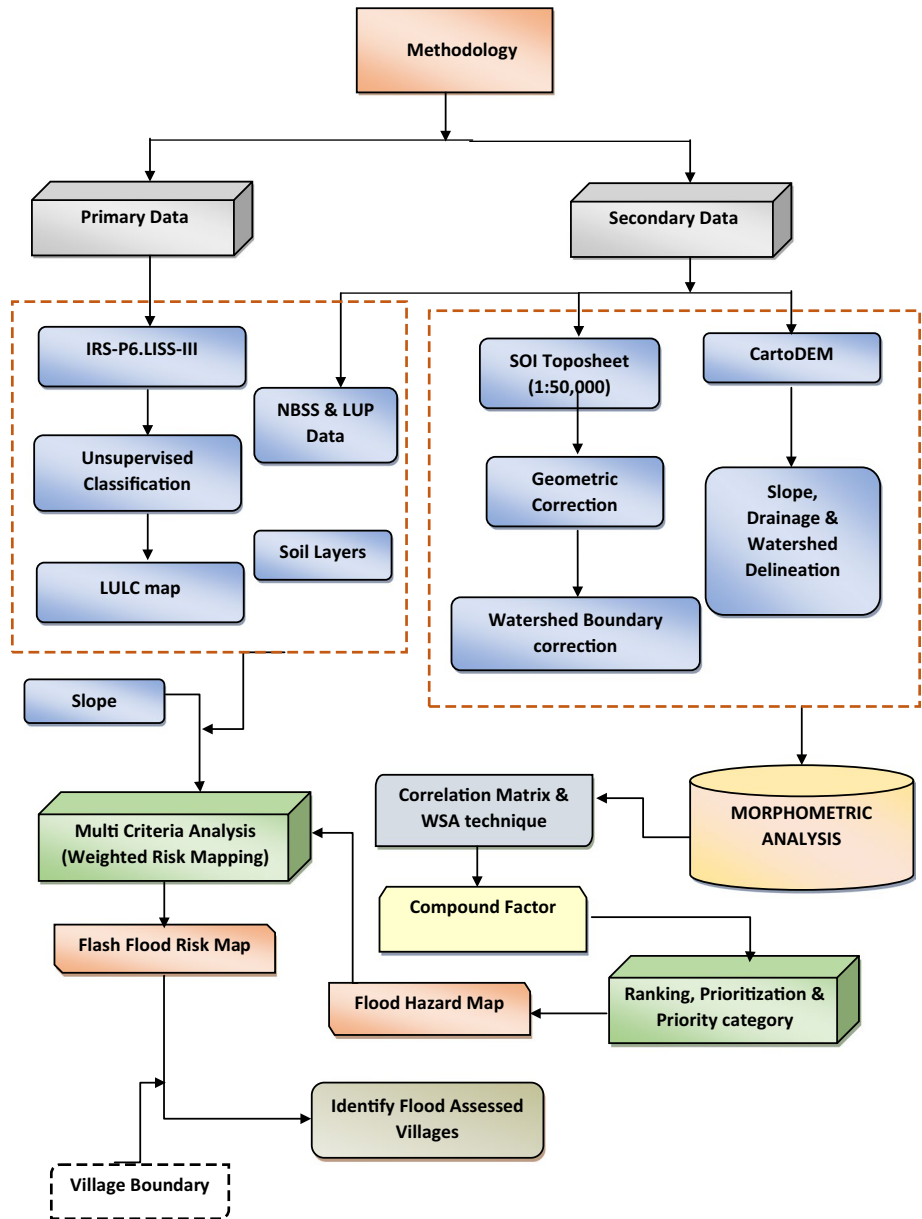


Fig. 3 Methodology chart

dangling, overlapping and intersection were removed. Automatic delineation of drainages was performed on CartoDEM with 30 m spatial resolution using ArcHydro tool in ArcMap 10.3, and the final drainage layer was prepared by comparing delineated drainage with the digitized drainage from SOI topographical sheets in GIS environment. Each stream was then given order number by following the stream ordering technique proposed by (Strahler

Table 1 LISS-III sensor specifications

Sensor	Resolution (m)	Swath width (km)	Sensor channels	Spectral bands (μm)
LISS-III	23.5	142	LISS-III-2	0.52–0.59
			LISS-III-3	0.62–0.68
			LISS-III-4	0.77–0.86
	50	148	LISS-III-5	1.55–1.70
	6	70	PAN	0.5–0.75

Source: <https://directory.eoportal.org/web/eoportal/satellite-missions/i/firs-p6>

Table 2 CartoDEM specifications

Parameter	Specifications
Image format	Geo-Tiff
Data type (DEM)	Signed short (2 bytes)
Data type (ortho-image)	Unsigned short (2 bytes)
Datum (planimetric and height)	WGS84
Projection	Geographic
Ellipsoidal height units	Meters
Generating agency	NRSC/ISRO
Copyright	NRSC/ISRO

Source: http://bhuvan-noeda.nrsc.gov.in/data/download/tools/document/cartodem_bro_final.pdf

1964) (Fig. 4). A delineated stream is of the order of 6, i.e., basin contains the stream of the highest order 6.

3.2 Digital elevation model and slope

CartoDEM with 30 m spatial resolution (Fig. 5) was utilized to derive slope map and to delineate watershed and micro-watershed boundaries. Slope map was categorized into five categories as shown in (Fig. 6); the study area is categorized into 9 equal categories, viz. level, nearly level, very gently sloping, gently sloping, moderately sloping, strongly sloping, very strongly sloping, extremely sloping, steep sloping and very steeply sloping as per the guidelines provided by Integrated Mission for Sustainable Development (IMSD) document (IMSD 1995). ArcHydro tool 10.3 was used for the automatic delineation of streams and micro-watershed boundaries for the study area.

3.3 Soil map

Soil layers were extracted using the data provided by the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), NRIS (National Resources Information System), and Department of Agriculture, Ahmedabad. Soil map at 1:50,000 scale was prepared (Fig. 7). Different types of soil have different capacities for retaining rainwater. In the study area, the dominant soil textures were considered for flood risk mapping. The detailed analysis of the soil map will be discussed in the analysis section. The study area comprises of

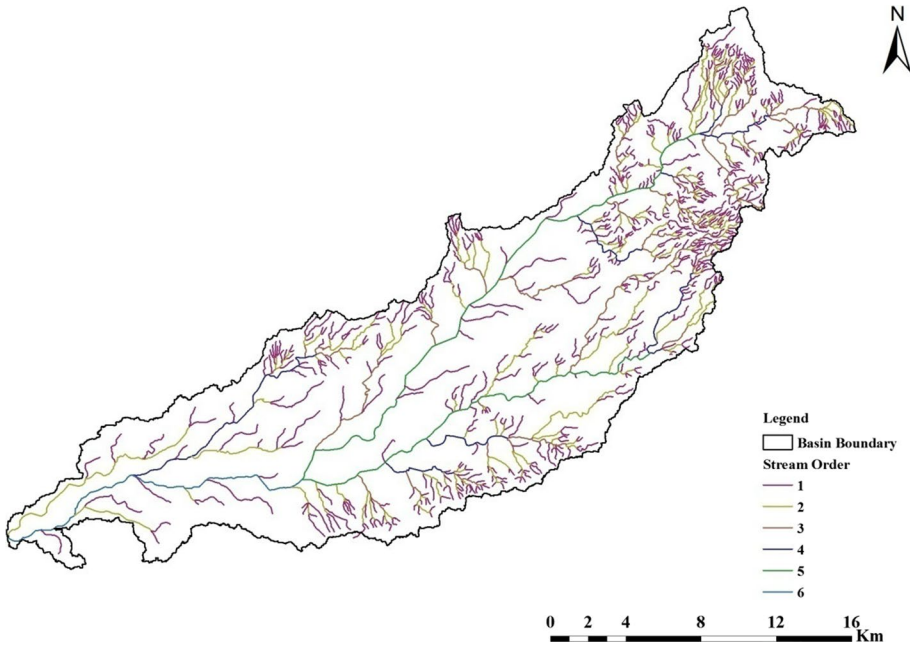


Fig. 4 Rel River drainage network map

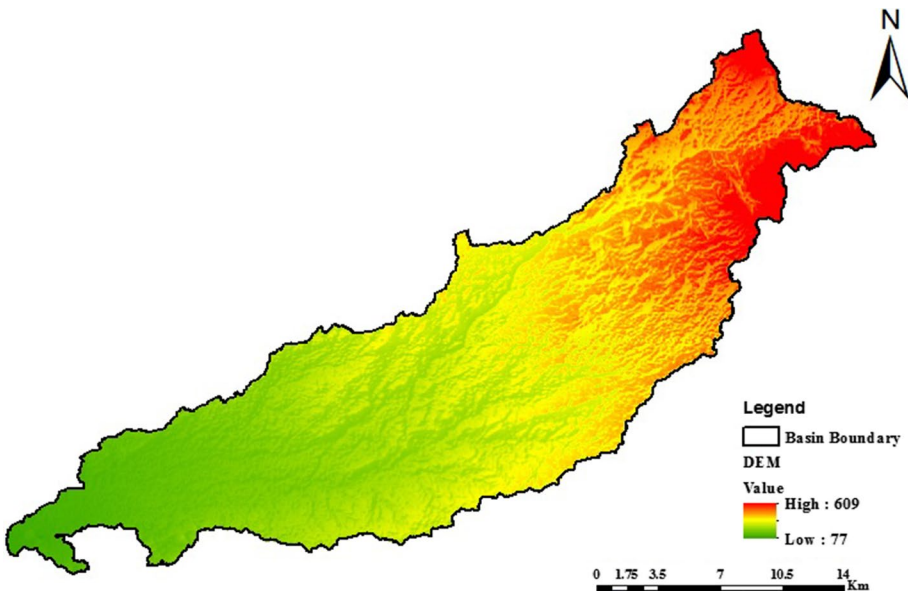


Fig. 5 Digital elevation model of Rel River catchment

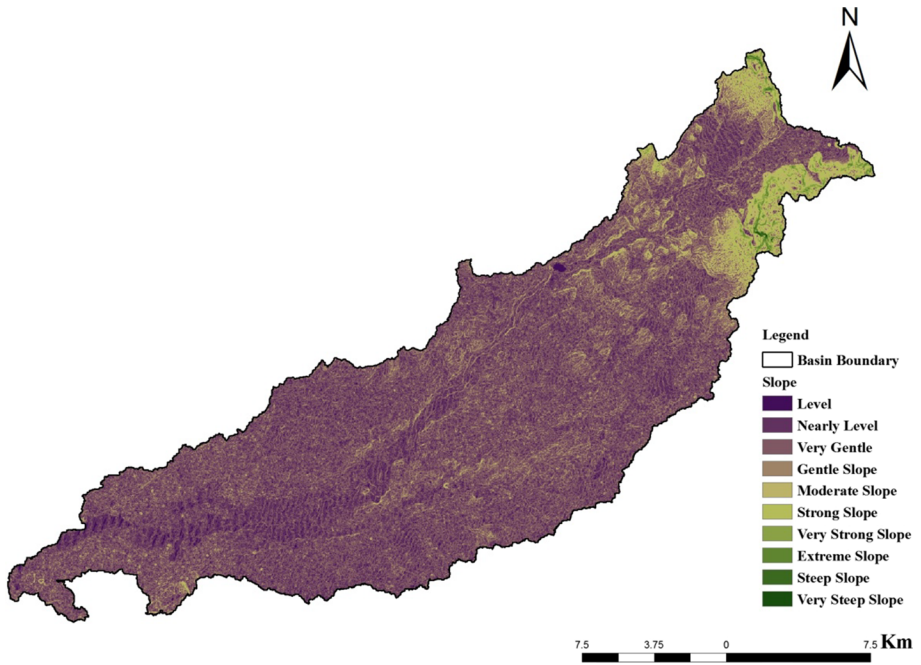


Fig. 6 Slope map

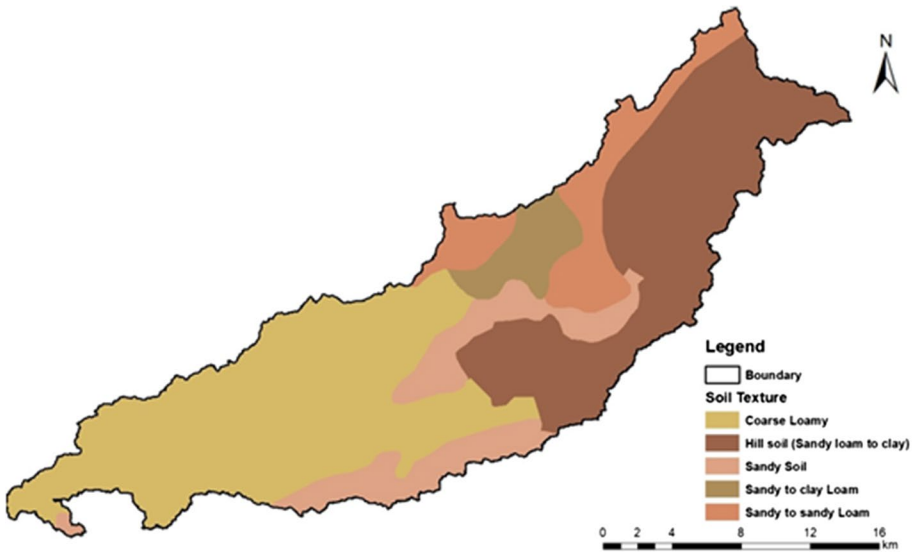


Fig. 7 Soil map

5 types of soil textures, namely sandy to sandy loam, sandy to clay loam, hill soil (sandy loam to clay), coarse loamy and sandy soil.

3.4 Morphometric parameters

Basin morphology is an important aspect to understand the river morphology. Morphologic parameters are divided in 3 categories, i.e., basic, linear and shape parameters. The area (A), perimeter (P), length (L), number of streams (N), length of basin (L_b) are included in basic parameters and calculated from the drainage layers and micro-watersheds, whereas linear and shape parameters were calculated based on the formula suggested by (Bhatt and Ahmed 2014; Horton 1945; Kumar et al. 2000; Miller 1953; Nooka Ratnam et al. 2005; Patel et al. 2012; Schumm 1956; Verstappen 1983) (Table 3). Calculated values of each morphometric parameter of Rel River basin for each micro-watershed are shown in Table 4.

3.4.1 Ranking, prioritization and flood hazard zone mapping on the basis of morphometric analysis

Every watershed has unique characteristics and thus behaves differently, and the critical watersheds have to be prioritized for the flood hazard mapping. In the present study, the Rel River basin was divided into 52 micro-watersheds. The various morphometric parameters mentioned in the previous section were used to prioritize each micro-watershed for their preferential risk assessment. Runoff potential has a direct relationship with the morphometric parameters such as drainage density (D_d), stream frequency (F_w), bifurcation ratio (R_b), texture ratio (T), elongation ratio (R_e) and infiltration number (I_f) (i.e., higher the values of these parameters, the higher the runoff potential of the watershed and vice versa). Thus, the rating was given by providing the highest priority, i.e., 1 having a maximum value of the parameter, and the lowest priority, i.e., 52 rank for having a minimum value of the parameter, whereas some parameters such as length of overland flow (L_o), circularity ratio (R_c), form factor (R_f), shape factor (B_s), compactness coefficient (C_c) and time of concentration (T_c) have an inverse relationship with runoff potential. Thus, inverse rating was given, i.e., 1 for a minimum value and 52 for a maximum value of the parameter (Table 5).

After the ranking, each morphometric parameter was given a weight and correlation matrix was computed based on WSA technique (Table 6). Hazard zone map was prepared on the basis of the compound factor value and their weights obtained using cross-correlation analysis of these parameters to give a compound factor for the final prioritization of micro-watersheds into hazard-prone areas. The mathematical expression for compound factor is written as (Aher et al. 2014; Malik et al. 2019):

$$FHV = PPR_{MP} \times W_{MP} \quad (1)$$

where FHV = flood hazard vulnerability, PPR_{MP} = preliminary priority rank based on morphometric parameter and W_{MP} = weight of morphometric parameter obtained using cross-correlation analysis.

The final ranking was made on the basis of FHV in such a way that the minimum value was given the priority rank 1, next minimum value was given priority rank of 2, and so on for all the micro-watersheds. A hazard scale number starting from 1 (very low) to 5 (very high) has been assigned to all the micro-watersheds. In this way, all the micro-watersheds have been categorized into 5 zones from very low to very high and their area was calculated. Categories are given in Table 7.

Table 3 Morphometric parameters with references

Sr. no.	Morphometric parameters	Formula	Reference
1	Area of the basin	$A = \text{Area of the basin in km}^2$	Nookaratnam et al. (2005)
2	Perimeter of basin	$P = \text{Perimeter in km}$	Nookaratnam et al. (2005)
3	Total no. of streams Total no. of first-order streams	$N = \text{No. of streams}$ $N1 = \text{Total no. of first-order streams}$	Nookaratnam et al. (2005)
4	Stream order (u)	Hierarchical rank	Strahler (1964)
5	Basin length (L_b)	$L_b = 1.312 * A^{0.568}$ where $L_b = \text{length of basin (km)}$ $A = \text{area of basin (km}^2)$	Nookaratnam et al. (2005)
6	Stream length (L)	Length of the stream	Horton (1945)
7	Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1} + 1$ where $R_b = \text{bifurcation ratio}$ $N_u = \text{total number of stream segments of order "u"}$ $N_{u+1} + 1 = \text{number of segment of next higher order}$	Schumm (1956)
8	Drainage density (D_d)	$D_d = L_u/A$ where $D_d = \text{drainage density}$ $L_u = \text{total stream length of all orders}$ $A = \text{area of the basin}$	Horton (1945)
9	Stream frequency (F_u)	$F_u = N_u/A$ where $F_u = \text{total number of streams of all orders}$ $A = \text{area of the basin (km}^2)$	Horton (1945)
10	Texture ratio (T)	$T = N_u/P$ where $N_u = \text{total number of streams of all orders}$ $P = \text{perimeter (km)}$	Horton (1945)
11	Length of overland flow (L_o)	$L_o = 1/D * 2$ where $L_o = \text{length of the overland flow}$ $D = \text{drainage density}$	Horton (1945)
12	Form factor (R_f)	$R_f = A/L_{b2}$ where $R_f = \text{form factor}$ $A = \text{area of the basin (km}^2)$ $L_{b2} = \text{square of the basin length}$	Horton (1945)
13	Shape factor (B_s)	$B_s = L_b^2/A$ where $B_s = \text{shape factor}$ $A = \text{area of the basin (km}^2)$ $L_{b2} = \text{square of the basin length}$	Nookaratnam et al. (2005)
14	Elongation ratio (R_e)	$R_e = (2/L_b) * (A/P)^{1/2}$ where $R_e = \text{elongation ratio}$ $L_b = \text{length of basin (km)}$ $A = \text{area of the basin (km}^2)$	Schumm (1956)
15	Compactness constant (C_c)	$C_c = 0.2821P/P^2$ where $C_c = \text{compactness ratio}$ $P = \text{perimeter of the basin (km)}$	Horton (1945)
16	Circularity ratio (R_c)	$R_c = 4\pi A/P^2$ where $R_c = \text{circularity ratio}$ $A = \text{area of the basin (km}^2)$ $P = \text{perimeter (km)}$	Miller (1953)

Table 3 (continued)

Sr. no.	Morphometric parameters	Formula	Reference
17	Infiltration number (I_f)	$I_f = F_s \times D_d$ where I_f = infiltration number F_s = stream frequency D_d = drainage density	Faniran (1968)

3.4.2 Multi-criteria analysis for flood risk mapping

Flood relief package allocation after the disaster is a very complex process, and it involves various surface parameters like LU/LC, soil, slope, drainage density, etc. Morphometry-based compound factor also plays a vital role in the assessment of flood risk zones. All these parameters have a great impact on flood monitoring and are necessary for flood risk assessment. In the present study, multi-criteria evaluation-based AHP (analytical hierarchical process) is used for risk mapping. Multi-criteria analysis is a structured decision-making tool for complex processes. It is used to describe an organized approach to determine overall preferences among all the alternative options with a view to rank them from the most important to least important for a particular problem. AHP was introduced in mid-1970s by Saaty and Vargas (1980). It involves the pairwise comparison of each factor, relative to its importance, on a rating scale from 1 to 9, where 1 indicates an equal preference between two factors and 9 for a factor extremely favored over the other. The next step involves the normalization of the matrix which is worked out by summing the numbers in each column and each entry in the column is later divided by the column value to yield its normalized score (Kumar Pradhan et al. 2018).

The priorities of the criteria are estimated by the principal Eigen vector “e” of the matrix “M,” as:

$$M_e = \lambda_{\max} e \tag{2}$$

where λ_{\max} is the largest Eigen value of the matrix “M” and the Eigen vector “e.”

Then to make sure whether the original preference rating was consistent, consistency ratio (CR) is calculated. Generally, a CR of 0.1 or below is considered as acceptable and any higher value at any level indicates inconsistency and needs re-examination. In other words, CR value less than 0.1 implies the consistency of the criteria.

The CR and consistency index (CI) can be estimated as follows:

$$CR = \frac{CI}{RI} \tag{3}$$

$$CI = \frac{(\lambda_{\max} - n)}{(n - 1)} \tag{4}$$

where RI = random inconsistency and n = number of variables.

Table 4 Morphometric parameters for each micro-watershed

Watershed ID	R_b	D_d	F_s	T	L_o	R_f	B_s	R_c	C_c	R_c	T_c	I_f
1	1.23	1.48	3.28	0.23	0.74	0.49	2.03	0.79	2.00	0.25	5.00	4.84
2	2.46	2.35	5.35	0.73	1.18	0.49	2.04	0.79	2.06	0.24	1.31	12.60
3	2.00	0.81	0.83	0.15	0.41	0.49	2.05	0.79	2.02	0.24	1.53	0.68
4	1.75	1.68	2.27	0.36	0.84	0.48	2.08	0.78	1.97	0.26	1.10	3.80
5	1.25	1.41	1.24	0.15	0.70	0.48	2.08	0.78	1.92	0.27	0.86	1.75
6	1.88	2.14	3.18	0.54	1.07	0.48	2.08	0.78	1.82	0.30	3.71	6.81
7	1.63	2.13	4.63	0.44	1.06	0.48	2.09	0.78	2.20	0.21	1.01	9.85
8	1.00	0.57	0.24	0.07	0.28	0.48	2.09	0.78	1.98	0.26	4.83	0.14
9	0.50	1.13	0.70	0.06	0.56	0.48	2.10	0.78	2.22	0.20	5.76	0.79
10	0.94	1.14	1.64	0.05	0.57	0.48	2.10	0.78	2.61	0.15	0.57	1.88
11	0.75	0.77	0.89	0.06	0.39	0.47	2.11	0.78	2.14	0.22	6.37	0.69
12	0.50	1.21	0.66	0.06	0.61	0.47	2.11	0.78	2.40	0.17	10.02	0.80
13	1.60	3.08	5.83	0.99	1.54	0.47	2.12	0.77	1.85	0.29	3.45	17.97
14	2.40	2.56	6.67	1.32	1.28	0.47	2.13	0.77	1.66	0.36	0.22	17.09
15	4.14	3.19	9.34	2.05	1.59	0.47	2.14	0.77	1.54	0.42	0.64	29.79
16	0.75	0.57	0.79	0.05	0.28	0.47	2.15	0.77	2.65	0.14	2.76	0.45
17	2.00	1.20	1.17	0.18	0.60	0.47	2.15	0.77	2.70	0.14	6.93	1.41
18	1.00	1.07	1.15	0.11	0.54	0.46	2.16	0.77	2.22	0.20	2.00	1.23
19	2.80	2.30	4.51	0.73	1.15	0.46	2.20	0.76	2.23	0.20	0.12	10.36
20	0.50	0.73	0.49	0.06	0.36	0.45	2.20	0.76	2.00	0.25	0.02	0.36
21	1.63	4.79	12.19	2.05	2.39	0.45	2.20	0.76	2.17	0.21	6.99	58.39
22	1.63	1.67	1.95	0.32	0.83	0.45	2.20	0.76	2.49	0.16	0.16	3.25
23	0.67	1.07	0.81	0.04	0.53	0.45	2.20	0.76	2.53	0.16	10.06	0.86
24	2.72	2.35	4.13	0.73	1.17	0.45	2.22	0.76	2.27	0.19	0.39	9.69
25	1.79	3.19	9.24	1.73	1.59	0.45	2.23	0.76	2.20	0.21	5.35	29.43
26	3.10	2.91	6.74	1.37	1.45	0.45	2.23	0.75	1.82	0.30	0.20	19.60
27	2.17	2.24	2.68	0.53	1.12	0.45	2.25	0.75	1.81	0.30	0.03	5.99
28	0.50	0.62	0.41	0.04	0.31	0.44	2.25	0.75	2.82	0.13	9.14	0.26
29	1.79	3.32	6.75	1.15	1.66	0.44	2.25	0.75	2.46	0.16	6.87	22.38
30	2.02	2.51	3.70	0.79	1.25	0.44	2.27	0.75	1.81	0.30	0.21	9.27
31	1.43	2.00	3.37	0.46	1.00	0.44	2.27	0.75	2.40	0.17	9.84	6.73
32	1.90	1.84	2.95	0.47	0.92	0.43	2.30	0.74	2.07	0.23	9.76	5.43
33	1.20	1.63	1.27	0.24	0.81	0.43	2.31	0.74	2.45	0.17	5.78	2.06
34	2.89	2.48	5.47	1.06	1.24	0.43	2.31	0.74	1.79	0.31	8.27	13.54
35	1.14	1.33	1.70	0.39	0.66	0.43	2.32	0.74	1.92	0.27	8.81	2.25
36	1.33	1.03	0.77	0.18	0.51	0.43	2.32	0.74	2.05	0.24	13.33	0.79
37	3.59	1.65	3.12	0.59	0.82	0.43	2.33	0.74	2.18	0.21	9.19	5.14
38	1.96	1.07	1.66	0.28	0.54	0.42	2.36	0.73	2.50	0.16	9.93	1.78
39	0.67	0.78	0.46	0.07	0.39	0.42	2.38	0.73	2.32	0.19	8.92	0.36
40	4.54	3.32	6.70	1.52	1.66	0.42	2.39	0.73	2.28	0.19	0.12	22.22
41	1.86	1.23	1.39	0.24	0.62	0.41	2.42	0.73	2.31	0.19	0.96	1.72
42	1.98	2.50	5.88	1.46	1.25	0.41	2.43	0.72	2.06	0.24	7.53	14.71
43	1.56	2.60	5.29	0.82	1.30	0.41	2.46	0.72	3.37	0.09	17.25	13.76
44	1.25	1.12	0.50	0.10	0.56	0.41	2.46	0.72	2.38	0.18	10.00	0.56

Table 4 (continued)

Watershed ID	R_b	D_d	F_s	T	L_o	R_f	B_s	R_c	C_c	R_c	T_c	I_f
45	2.90	4.03	7.14	2.37	2.01	0.41	2.46	0.72	1.59	0.40	0.20	28.76
46	2.03	1.06	1.05	0.21	0.53	0.40	2.47	0.72	2.49	0.16	5.49	1.11
47	1.25	0.97	0.62	0.17	0.49	0.40	2.48	0.72	2.21	0.20	10.49	0.60
48	0.67	0.86	0.32	0.06	0.43	0.40	2.50	0.71	2.48	0.16	21.19	0.28
49	1.67	1.50	1.28	0.35	0.75	0.40	2.52	0.71	2.21	0.21	14.45	1.91
50	1.81	2.73	6.11	1.84	1.36	0.39	2.57	0.70	2.07	0.23	3.58	16.67
51	1.74	2.49	4.10	1.19	1.24	0.39	2.57	0.70	2.18	0.21	8.98	10.19
52	1.22	0.76	0.40	0.06	0.38	0.37	2.67	0.69	2.85	0.12	0.89	0.30

3.4.3 Flood relief package (FRP) allocation

As described in the previous section, flood risk assessment involves interactions of various complex processes such as LU/LC, soil, slope, drainage density and morphometry-based compound factor. In this process, risk map was prepared using the weighted sum approach where weights for each factor involved for risk assessment have been calculated using multi-criteria-based AHP process. In this process, instead of using compound factor, flood hazard map prepared using compound factor was used to assess risk map and in prioritizing the zoned for flood relief package allocation. Weightages assigned for each parameter are given in Table 8, which were utilized to create FRP map using the weighted sum approach as follows:

$$FRP = W_1 \times CF + W_2 \times Slope + W_3 \times LU/LC + W_4 \times D_d + W_5 \times Soil \tag{5}$$

where W_i =normalized weights calculated using AHP method given in Table 8.

4 Result and discussion

Watershed hydrology is greatly affected by its morphometry (Tucker and Bras 1998). Watershed morphometry provides a complete description of the linkages between different land surface processes and different components of the land system such as geomorphology, hydrology, geology and LC (Astaras and Soulakellis 1992). Moreover, the characteristic drainage system of a watershed has a strong impact on its infiltration capacity and runoff (Sharma et al. 1986). The runoff potential has a direct relationship with many of the morphometric parameters such as drainage density (D_d), stream frequency (F_u), bifurcation ratio (R_b), texture ratio (T), elongation ratio (R_e) and infiltration number (I_f), length of overland flow (L_o), circularity ratio (R_c), form factor (R_f), shape factor (B_s), compactness coefficient (C_c), infiltration number (I_f) and time of concentration (T_c) as per Tables 4 and 5. The significance of these parameters is discussed as follows:

4.1 Drainage density (D_d)

The D_d is a significant factor in controlling over the landscape runoff, and it influences on the flood peak discharges (Pallard et al. 2009; Yildiz 2004). The D_d values are normally

Table 5 Ranking of morphometric parameters

Watershed ID	R_b	D_d	F_u	T	L_o	R_f	B_s	R_e	C_c	R_c	T_c	I_f	CF	Rank
1	37	29	21	32	24	52	1	1	15	38	27	28	16.96	29
2	9	16	13	17	37	51	2	2	19	34	35	39	-18.42	43
3	14	45	39	37	8	50	3	3	16	37	34	10	39.57	23
4	24	24	26	26	29	49	4	4	12	41	36	27	6.70	33
5	34	30	34	38	23	48	5	5	10	43	40	20	27.19	26
6	19	20	22	20	33	47	6	6	8	45	29	33	-7.19	38
7	27	21	15	24	32	46	7	7	27	26	37	36	4.86	34
8	41	52	52	42	1	45	8	8	13	40	28	1	69.23	10
9	49	36	43	44	17	44	9	9	30	23	24	13	60.58	13
10	43	35	30	49	18	43	10	10	47	6	42	22	58.94	15
11	44	47	38	43	6	42	11	11	22	31	22	11	62.13	12
12	50	33	44	48	20	41	12	12	38	15	7	14	65.79	11
13	30	7	11	13	46	40	13	13	9	44	31	45	-23.34	46
14	10	11	8	9	42	39	14	14	3	50	44	44	-34.27	49
15	2	5	2	2	48	38	15	15	1	52	41	51	-52.20	52
16	45	51	41	50	2	37	16	16	48	5	32	7	87.68	4
17	15	34	35	34	19	36	17	17	49	4	20	18	47.12	20
18	42	39	36	39	14	35	18	18	31	22	33	17	56.68	17
19	7	18	16	18	35	34	19	19	32	21	50	38	-2.36	37
20	51	49	47	47	4	33	20	20	14	39	52	5	74.07	7
21	28	1	1	3	52	32	21	21	23	30	19	52	-30.66	48
22	29	25	27	28	28	31	22	22	44	9	48	26	35.02	24
23	46	40	40	51	13	30	23	23	46	7	6	15	77.20	6
24	8	17	17	16	36	29	24	24	33	20	43	35	0.53	35
25	22	6	3	5	47	28	25	25	26	27	26	50	-23.46	47
26	4	8	6	8	45	27	26	26	7	46	46	46	-35.05	50
27	11	19	25	21	34	26	27	27	6	47	51	31	-2.33	36
28	52	50	49	52	3	25	28	28	50	3	13	2	102.10	1
29	23	3	5	11	50	24	29	29	41	12	21	48	-11.57	41
30	13	12	19	15	41	23	30	30	5	48	45	34	-13.29	42
31	32	22	20	23	31	22	31	31	39	14	10	32	26.71	27
32	18	23	24	22	30	21	32	32	21	32	11	30	14.47	30
33	39	27	33	31	26	20	33	33	40	13	23	24	47.90	19
34	6	15	12	12	38	19	34	34	4	49	17	40	-19.85	44
35	40	31	28	25	22	18	35	35	11	42	16	25	31.59	25
36	33	42	42	35	11	17	36	36	17	36	4	12	57.65	16
37	3	26	23	19	27	16	37	37	24	29	12	29	12.54	31
38	17	38	29	29	15	15	38	38	45	8	9	21	50.66	18
39	47	46	48	41	7	14	39	39	36	17	15	6	86.12	5
40	1	4	7	6	49	13	40	40	34	19	49	47	-21.01	45
41	20	32	31	30	21	12	41	41	35	18	38	19	44.83	21
42	16	13	10	7	40	11	42	42	18	35	18	42	-10.78	40
43	31	10	14	14	43	10	43	43	52	1	2	41	17.15	28
44	35	37	46	40	16	9	44	44	37	16	8	8	73.72	8

Table 5 (continued)

Watershed ID	R_b	D_d	F_u	T	L_o	R_f	B_s	R_e	C_c	R_c	T_c	I_f	CF	Rank
45	5	2	4	1	51	8	45	45	2	51	47	49	-40.59	51
46	12	41	37	33	12	7	46	46	43	10	25	16	60.27	14
47	36	43	45	36	10	6	47	47	29	24	5	9	73.27	9
48	48	44	51	46	9	5	48	48	42	11	1	3	96.35	3
49	26	28	32	27	25	4	49	49	28	25	3	23	40.89	22
50	21	9	9	4	44	3	50	50	20	33	30	43	-10.21	39
51	25	14	18	10	39	2	51	51	25	28	14	37	8.07	32
52	38	48	50	45	5	1	52	52	51	2	39	4	100.02	2

high in the regions of impermeable subsurface material, sparse vegetation and mountainous relief that implies on high flood volumes (Pallard et al. 2009). The low D_d values represent permeable subsurface material, good vegetation cover and low relief cause low flood volumes (Pallard et al. 2009). The drainage density indicates the closeness of streams to each other and thus determines the time travel by the water to pass that area. In the Rel River micro-watersheds, the D_d values range from 0.57 to 4.79 km/km² (Table 4). The watersheds 21 and 45 correspond to very high drainage density while 15, 25, 26, 40 and 49 correspond to high drainage density. All these fall under high relief category having impermeable subsurface material and thus contribute more runoff in a short period of time. While the watersheds near at low level and near to outlet point have low drainage density, watersheds in this category are at higher risk of flood hazard as it takes more time for water to pass through these areas due to low elevation and having good amount of vegetation and other land surface which act as a barrier to water flow, and thus, one can categorize high drainage density at low risk of flood hazard and vice versa. About 57.74% of the area has high to very high drainage density which is in the northern region of the basin (Table 9, Fig. 8).

4.2 Bifurcation ratio (R_b)

In case of floods, the R_b plays an important role in control over the peak of the runoff hydrograph (Chorley 1969; Jain and Sinha 2003). It is calculated by dividing total streams in the lower by the total streams in the higher of the two orders. The R_b of 2 is obtained for flat terrain and 3–4 for mountainous or highly dissected terrain (Horton 1945). The R_b values of the catchments are varying from 0.50 to 4.54 indicating the higher values of R_b (Table 4). This higher value of R_b indicates mature topography with a higher degree of drainage integration and attains peak discharge during the period of floods (Eze and Efiiong 2010).

4.3 Stream frequency (F_u)

F_u is an interlinking factor in predicting peak flood discharge (Eze and Efiiong 2010; Patton and Baker 1976). Stream frequency is highly correlated with permeability, infiltration capacity and relief of watersheds (Montgomery and Dietrich 1989, 1992). Generally, high F_u is related to impermeable subsurface material, sparse vegetation, high relief conditions and low infiltration capacity (Reddy et al. 2004; Shaban et al. 2005), while low value

Table 6 Correlation of morphometric parameters for each micro-watershed

Correlation parameter	R_b	D_d	F_u	T	L_o	R_f	B_s	R_e	C_c	R_c	T_C	I_f
R_b	1.000	0.666	0.707	0.778	-0.666	0.102	-0.102	-0.102	0.411	-0.411	-0.375	-0.691
D_d	0.666	1.000	0.954	0.935	-1.000	0.053	-0.053	-0.053	0.401	-0.401	-0.270	-0.979
F_u	0.707	0.954	1.000	0.935	-0.954	-0.030	0.030	0.030	0.412	-0.412	-0.316	-0.991
T	0.778	0.935	0.935	1.000	-0.935	0.178	-0.178	-0.178	0.487	-0.487	-0.242	-0.941
L_o	-0.666	-1.000	-0.954	-0.935	1.000	-0.053	0.053	0.053	-0.401	0.401	0.270	0.979
R_f	0.102	0.053	-0.030	0.178	-0.053	1.000	-1.000	-1.000	-0.274	0.274	0.375	0.004
B_s	-0.102	-0.053	0.030	-0.178	0.053	-1.000	1.000	1.000	0.274	-0.274	-0.375	-0.004
R_e	-0.102	-0.053	0.030	-0.178	0.053	-1.000	1.000	1.000	0.274	-0.274	-0.375	-0.004
C_c	0.411	0.401	0.412	0.487	-0.401	-0.274	0.274	0.274	1.000	-1.000	-0.362	-0.409
R_c	-0.411	-0.401	-0.412	-0.487	0.401	0.274	-0.274	-0.274	-1.000	1.000	0.362	0.409
T_C	-0.375	-0.270	-0.316	-0.242	0.270	0.375	-0.375	-0.375	-0.362	0.362	1.000	0.290
I_f	-0.691	-0.979	-0.991	-0.941	0.979	0.004	-0.004	-0.004	-0.409	0.409	0.290	1.000
Some of correlations	1.317	1.253	1.365	1.351	-1.253	-0.371	0.371	0.371	0.813	-0.813	-0.018	-1.337
Total	3.049	3.049	3.049	3.049	3.049	3.049	3.049	3.049	3.049	3.049	3.049	3.049
Weight	0.4318	0.411	0.4477	0.4432	-0.411	-0.122	0.1217	0.1217	0.2666	-0.267	-0.006	-0.438

Table 7 Flood hazard zone

Sr. no.	Category	Priority level	MWS- ID	Area (km ²)	Area (%)
1	Very low	−52.20 to −21.34	15, 45, 26, 14, 21, 25, 13, 40	59.33	13.43
2	Low	−21.34–9.52	34,2, 30, 29, 42, 50, 6, 19, 27, 24, 7, 4, 51	109.71	24.84
3	Medium	9.52–40.38	37, 32, 1, 43, 31, 5, 35, 22, 3	65.10	14.74
4	High	40.38–71.24	49, 41, 17, 33, 38, 18, 36, 10, 46, 9, 11, 12, 8	103.00	23.32
5	Very high	71.27–102.10	47, 44, 20, 23, 39, 16, 48, 52, 28	104.41	23.64

Table 8 Pairwise comparison matrix to calculate normalized weights of each parameter for FRP allocation using AHP method

Parameters	FHV	Slope	LU/LC	Drainage density	Soil types	Normalized weights
FHV	1	3	5	7	7	0.51
Slope	1/3	1	3	5	5	0.25
LU/LC	1/5	1/3	1	3	3	0.12
Drainage density	1/7	1/5	1/3	1	1	0.052
Soil types	7/7	1/5	1/3	1	1	0.052
CR	0.0306					

Table 9 Flood hazard risk as per drainage density

Category	Area (km ²)	Proportion	Proportion (%)
Very low	20.1	0.045516	4.551630435
Low	41.5	0.093976	9.397644928
Moderate	125	0.283062	28.30615942
High	173	0.391757	39.17572464
Very high	82	0.185688	18.56884058
Total	441.6	101	100

corresponds to low relief and permeable subsurface material. In Rel basin, F_u values for micro-watershed range between 0.24 and 12.19 per km² (Table 4). High F_u values specifies that it has rocky terrain and thus has very low infiltration capacity; hence, it is associated with early discharge peak that could result in flashfloods thus were given low rank and low values were assigned high ranks (i.e., ranks from 1 to 52 for high F_u to Low F_u values, respectively).

4.4 Texture ratio (T)

The texture ratio is influenced by numerous natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development (Smith 1950). The soft and weak rocks unprotected by vegetation produce a fine texture, whereas massive

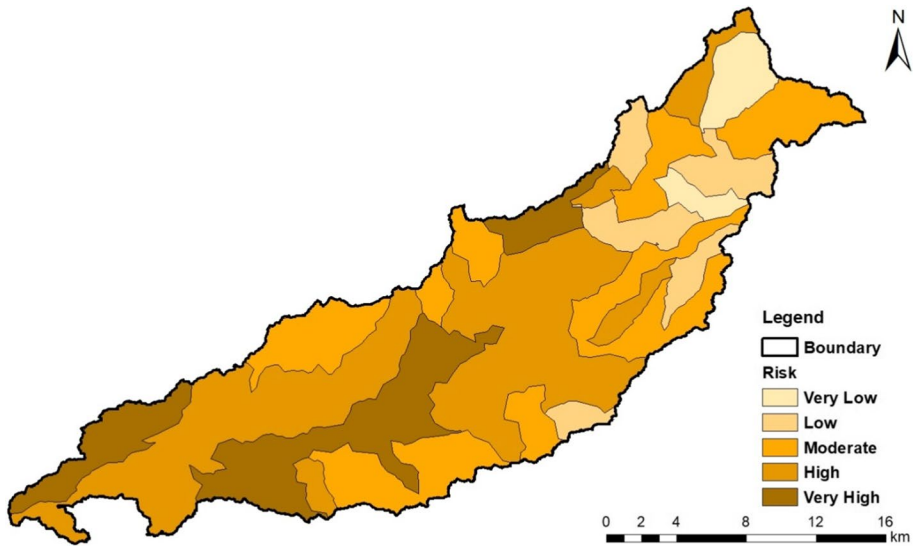


Fig. 8 Risk map as per drainage density

and resistant rocks cause coarse texture (Sreedevi et al. 2009). According to (Altaf et al. 2013), the T is classified as very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8) and very fine (>8). In the study area, the drainage texture varies from 0.04 to 2.37 indicating very coarse to a coarse texture (Table 4). According to this classification, very coarse texture watersheds have large basin lag time followed by coarse, fine and very fine texture classes, making its downstream vulnerable to flooding. The micro-watersheds having the highest T values cause peak discharge during the period of rainfall and thus were ranked in ascending order from 1 to 52 for highest to lowest corresponding texture values.

4.5 Elongation ratio (R_e)

Elongation ratio (R_e) is defined as the ratio between the diameter of the circle of the area as represented by the drainage basin and the maximum basin length (Schumm 1956). (Strahler 1964) stated that R_e values vary generally between 0.6 and 1.0 over a wide range of climate and geological conditions. Values close to 1.0 are characteristic of regions with very low relief, whereas values in the range of 0.6–0.8 are normally diagnostic of watersheds with high relief and steep slopes. Where R_e approaches 1.0, the shape of the drainage basin approaches a circle (Schumm 1956). In the present study, R_e varies from 0.69 to 0.79; hence, high R_e value attains hydrograph peak quicker and thus increases its vulnerability to flooding (Table 4).

4.6 Length of overland flow (L_o)

Length of overland flow is one of the most important independent variables affecting both hydrologic and hydrographic developments of drainage basins (De Vaumas 1961). Length of overland flow (L_o) for the study area varies from 0.28 to 2.39. Micro-watersheds with higher L_o values indicate that it has a gentle slope and longer flow paths, which means

surface runoff will take less time to reach the outlet, thereby making more vulnerable to the flooding. Thus, rank 1 was assigned to a maximum value (i.e., 2.39) corresponding to watershed no 21 and rank 52 for the minimum value (i.e., 0.28) corresponding to watershed no. 8 (Table 4).

4.7 Form factor (R_f)

R_f represents the shape or outlines of a basin and is useful in predicting the flow intensity of a catchment. It is directly linked to peak discharge (Gregory and Walling 1973; Horton 1945). The R_f values for the basin range from 0.37 to 0.49. Low R_f value reveals that it has less side flow for a shorter duration and high main flow for longer duration and vice versa (Reddy et al. 2004). Thus, micro-watersheds from minimum to maximum value were assigned ranks 1–52, respectively. A higher value indicates a more elongated shape of the respective micro-watershed as compared to other micro-watersheds (Table 4).

4.8 Shape factor (B_s)

Shape factor (B_s) is calculated by dividing the square of the length of a basin by the area of the basin (Horton 1945) and is considered in inverse proportion to the form factor (R_f). The shape of the drainage basin along with the length and relief affects the rate of water and sediment yield. B_s values for the catchments range from 2.03 to 2.67 with an average of 2.35; thus, it is expected to have the shorter basin lag time.

4.9 Compactness constant (C_c)

Compactness constant for the study area varies from 1.54 to 3.37. Compactness constant expresses the relationship of a basin with that of a circular basin having the same area. Circular basin yields the shortest time of concentration before peak flow occurs in the basin. If $C_c = 1$, then the basin completely behaves as a circular basin. $C_c > 1$ indicates that the basin has more deviation from the circular nature. Higher values of C_c indicate more deviation from the circular nature; therefore, it will have the longest time of concentration before attaining peak flow (Table 4).

4.10 Circularity ratio (R_c)

Circularity ratio (R_c) refers to the ratio of catchment area (A) to the area of the circle having the same circumference as the perimeter of the catchment (Miller 1953). R_c is controlled by the length and frequency of the streams, geological structures, land use, land cover, climate, relief and slope steepness of the catchment. The circularity ratio (R_c) of the studied micro-watersheds ranges from 0.09 to 0.42 with a mean 0.25 indicating no circular shape (circular when $R_c = 1$) but elongated. This geometry suggests that the estimated time for the flow to accumulate in the main channel is more than that required in the circular sub-basins (Abdelkareem 2017; Miller 1953).

Table 10 Slope categories

Category	Area (km ²)	Proportion	Proportion (%)
Very low	21.899	0.049	4.96
Low	18.22	0.041	4.12
Moderate	34.65	0.078	7.84
High	84.76	0.192	19.20
Very high	281.92	0.638	63.86
Total	441.44	101	100

Table 11 Risk based on soil infiltration capacity

Category	Area (km ²)	Proportion	Proportion (%)
Very low	53.452	0.121049342	12.10493419
Low	46.4	0.105079126	10.50791264
Moderate	181.69	0.411461777	41.14617775
High	139.2	0.315237379	31.52373792
Very high	20.83	0.047172375	4.717237506
Total	441.572	101	100

4.11 Time of concentration (T_c)

The T_c is the time taken by water to travel from the source to its outlet from the basin. The highest T_c value represents the greatest length of time for water to travel from the most distant point of the catchment to its outlet (Ozdemir and Bird 2009). The T_c value varies from 21.19 to 0.02 (Table 4); hence, micro-watershed 48 has taken the highest time for travel of water to reach at its outlet.

4.12 Infiltration number (I_f)

Infiltration number (I_f) of a watershed gives an idea about the infiltration characteristics of the catchment. It is inversely proportional to the infiltration capacity of the basin (Romshoo et al. 2012). The higher the I_f , the lower will be the infiltration and the higher runoff (Bhatt and Ahmed 2014). The I_f value varies from 0.14 to 58.39 (Table 4).

4.13 Slope

Higher the slope, the higher will be the runoff and less will be the flood hazard severity. The slope of the study area was divided into five categories from very low slope to a very high slope. Around 80% of the area falls under high to a very high category which is because of the Aravalli Hills in the northern region of the basin (i.e., from the source point of the basin). The area statistics for slope is given in Table 10.

4.14 Soil

As discussed in the methodology section, the area consists of five categories of soil namely sandy to sandy loam, sandy to clay loam, hill soil (sandy loam to clay), coarse loamy and sandy soil, and based on their infiltration capability the soil layer has also been divided into very low to very high category. The infiltration capacity of soil plays a vital role in the water absorption during the rainy season. High infiltration capacity will lead to low flood risk, and thus, very low category indicates the areas under high flood hazard zone. Approx. 63.75% of the area (Table 11) falls under very low to moderate risk. This mostly covers the lower basin and the northeastern part of the basin (Fig. 7).

4.15 Land use/land cover analysis

LU/LC can drive both positive and negative impacts on water resources, hydrologic processes (interception, infiltration, sediment yield, surface runoff, evapotranspiration, groundwater, etc.) and in soil nutrient studies (Kumar et al. 2018b). Different LU/LC conditions can be responsible for different hydrologic responses of a basin (Lin et al. 2009), and thus, one cannot use the same LU/LC condition as used in previous basin to predict hydrologic response for the next basin. Moreover, LU/LC is also responsible for the stream generation capacity of a basin. The stream generation capacity of a basin depends upon the vegetation as well as spatiotemporal variations in other LU/LC classes (Molina-Navarro et al. 2014). For instance, vegetation has a significant impact on the infiltration capacity of the soil. It increases the infiltration capacity exponentially, but at the same time it resists the flow of water and hence increases the lag time of water to reach the outlet point. Thus, high vegetation will reduce the runoff vulnerability and thus will lower the flood risk. On the contrary, the impermeable surfaces like built-up (urban), barren, etc., have the potentiality of high runoff. Hence, based on the significance of all the LU/LC parameters on flood hazard (as

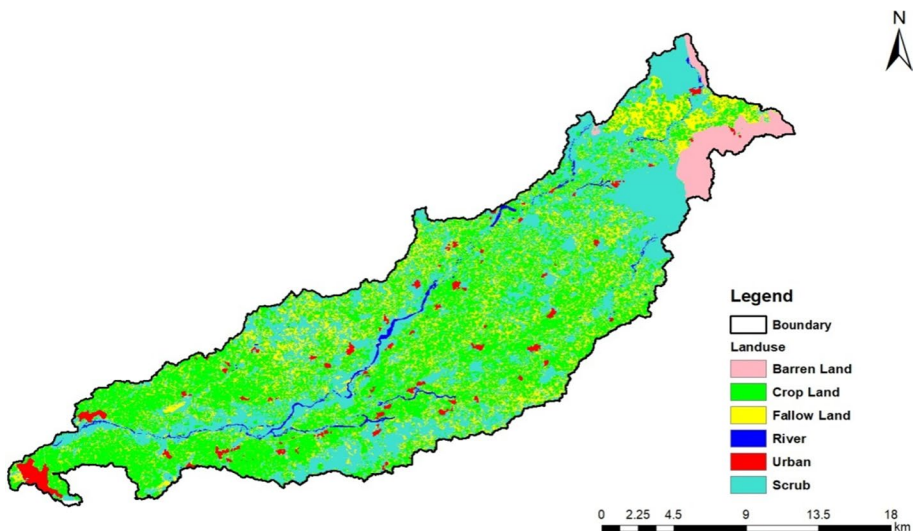


Fig. 9 Land use/land cover map

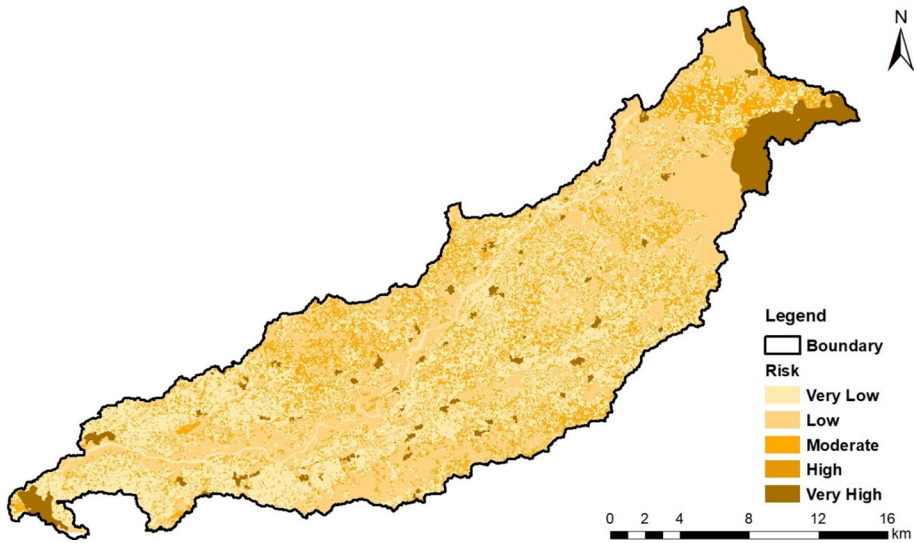


Fig. 10 Land use/land cover risk map

Table 12 Flood hazard risk as per land use/land cover

Category	Area (km ²)	Proportion	Proportion (%)
Very low	184.6	0.418025	41.80253623
Low	147	0.33288	33.28804348
Moderate	86	0.194746	19.47463768
High	9	0.02038	2.038043478
Very high	15	0.033967	3.39673913
Total	441.6	101	100

per the literature), LU/LC layer has also been categorized into five categories, i.e., very low risk to very high risk. The LU/LC map, as well as the LU/LC risk map, is shown in Figs. 9 and 10 while the area statistics of these categories are given in Table 12.

4.16 Ranking and flood hazard analysis

Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface, shape and dimension of its landforms; it can be used to describe the basin characteristics. Morphometric parameters were used to understand the basin characteristics, and based on these parameters, compound factor was calculated. The procedure of this has already been discussed earlier in the paper.

The priority ranks of micro-watersheds were determined on the basis of compound factor (Table 5), which was calculated using Eqs. 1, 6. The value of weights assigned to a morphometric parameter was calculated by dividing the sum of correlation coefficient of each parameter by the grand total of correlations (Table 6). By assigning the weights to different parameters, a model was formulated to assess the final priority ranking. The compound factor for watershed prioritization was computed as:

$$\begin{aligned} \text{Compound Factor} = & (0.43 \times R_b) + (0.41 \times D_d) + (0.44 \times F_u) + (0.44 \times T) + (-0.41 \times L_o) \\ & + (-0.12 \times R_f) + (0.12 \times B_s) + (0.12 \times R_c) + (0.26 \times C_c) \\ & + (-0.26 \times R_c) + (-0.006 \times T_c) + (-0.43 \times I_f) \end{aligned} \tag{6}$$

From the group of these micro-watersheds, the first rank was assigned to the micro-watershed having the highest compound factor and so on. The ranking of all the parameters is given in Table 5.

The compound factor was further categorizing the micro-watersheds into very low, low, moderate, high and very highly prone zones of flood hazard (Table 7). Based on the compound factor value, all the 52 micro-watersheds of Rel River basin were classified into five priority categories such as: (i) very low (−52.20 to −21.34); (ii) low (−21.34–9.52); (iii) medium (9.52–40.38); (iv) high (40.38–71.24); and (v) very high (71.27–102.10) as given in Table 7.

Mostly the watersheds near to the river and the low-lying areas, i.e., those near the outlet of the basin having a low slope, have less lag time and so are more prone toward flood hazard. Out of 52 micro-watersheds, Table 7 shows that the nine micro-watersheds (MWS 47, 44, 20, 23, 39, 16, 48, 52, 28) were under very high category, thirteen micro-watersheds (MWS 49, 41, 17, 33, 38, 18, 36, 10, 46, 9, 11, 12, 8) under high category, nine micro-watersheds (MWS 37, 32, 1, 43, 31, 5, 35, 22, 3) under medium category, thirteen micro-watersheds (MWS 34, 2, 30, 29, 42, 50, 6, 19, 27, 24, 7, 4, 51) under low category and eight micro-watershed (MWS 15, 45, 26, 14, 21, 25, 13, 40) under very low category. The final priority category map of 52 micro-watersheds is shown in Fig. 11, which reveals that the percentage of the area of micro-watersheds under very high category is 23.64%, a high category is 23.32%, a medium category is 14.74%, a low category is 24.84% and

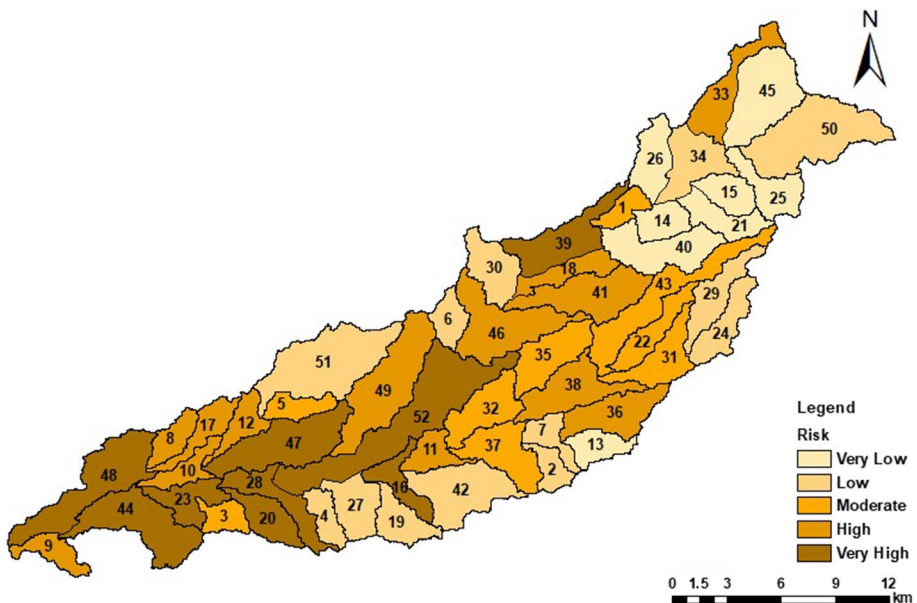


Fig. 11 Flood hazard zone map of Rel River micro-watersheds

Table 13 Normalized weights for each factor for risk mapping based on AHP method

	cf	Slope	LU/LC	D_d	Soil	Normalized weights
cf	1.0000	3.0000	5.0000	7.0000	7.0000	0.512
Slope	0.3333	1.0000	3.0000	5.0000	5.0000	0.259
LU/LC	0.2000	0.3333	1.0000	3.0000	3.0000	0.122
D_d	0.1429	0.2000	0.3333	1.0000	1.0000	0.052
Soil	0.1429	0.2000	0.3333	1.0000	1.0000	0.052

Table 14 Consistency ratio of the method

λ_{\max}	CI	RI	CR
5.1370	0.0342	1.1200	0.0306

a very low category is 13.43%. Dhanera City is located at the outlet of the basin and so comes under high-risk-prone area. The spatial distribution of all the areas covered under these categories is shown in Fig. 11, and the area statistics of flood hazard category is shown in Table 7.

4.17 Flood risk analysis

After the identification of flood hazard-prone zones, the other factors such as soil, land use/land cover, drainage density and slope were combined with the flood hazard map by and multi-criteria analysis was performed to find the exact risk zones of the study area. The weights used for each factor for the multi-criteria analysis were calculated using AHP method with the consistency ratio around 0.0306 (< 0.1) shown in Tables 8, 13 and 14, which indicates good consistency of the method and the ranks (rating) given to each factor were significant for flood risk mapping. The rating factor varies from 1 to 9 where 9 reflects the higher influence on soil erosion and 1 for least or minimum influence on soil erosion (Maurya et al. 2016). Table 8 shows the computation of normalized weight for each factor based on assigned ratings and CR ratio of the method.

4.18 Flood relief package (FRP) allocation

The computed weights were used to obtain the flood risk map, and village boundary was further overlaid on the map to find exactly those areas that fall within the Banaskantha District of Gujarat. The risk map (Fig. 12) was then assessed to find the risk zones, and their area proportion was calculated (Table 15).

FRP layer was computed using the equation:

$$\text{FRP} = 0.513 \times \text{CF} + 0.26 \times \text{Slope} + 0.123 \times \text{LU/LC} + 0.0526 \times D_d + 0.0526 \times \text{Soil} \quad (7)$$

where FRP=flood relief package, CF=compound factor, LU/LC=land use and land cover, D_d =drainage density.

Out of 39 villages, 17 villages including Dhanera, Fatepura, Malotra, Sotwada, Valer, Rampura Mota, Runi, Dedha, Sabawadi, Ravi, Vasda, Rampura along with the villages

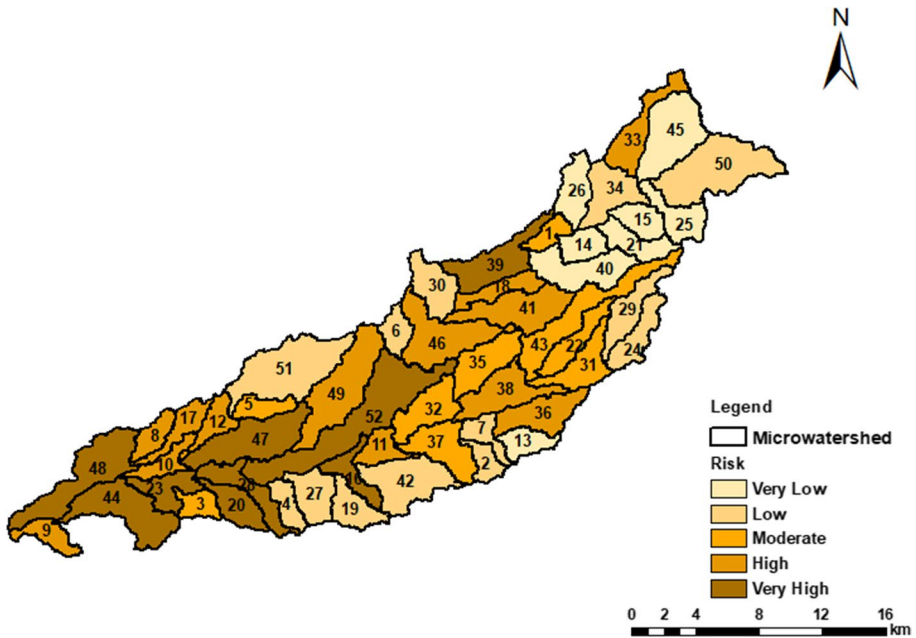


Fig. 12 Risk map of Rel River micro-watersheds

Table 15 Proportion of area under risk

Category	Area (sq.km)	Proportion	Proportion (%)
Very low	89.214048	0.202246	20.22462704
Low	84.735616	0.192094	19.20937642
Moderate	102.84448	0.233146	23.31461577
High	106.5778	0.24161	24.16095115
Very high	57.743968	0.130904	13.09042962
Total	441.115912	101	100

whose 50% of the area (namely Mewada, khimat, Rajoda, Alwada, Vaktapura) fall under high- to very high-risk category; all these villages together cover the area proportion of 37.25% while the villages Voda, Nana Meda, Janali, Anapurgarh, Anapura chhota, Kundli, Mewada, Khangan, Bhatram, Sodal, Dhaniyawada, Vachhol on both sides of the river with the 23.32% of the total geographical area fall under moderate category. The area proportion under risk is given in Table 15.

Final flood relief package can be allocated to each village that falls within these categories by using this area statistics (Fig. 13). For example, the amount granted for after disaster event may be allocated to each village by the percentage of the severity of the disaster on them which can be computed by multiplying the total amount to be allocated with the area proportion of each risk category for that particular village. This will be justifying the distribution of flood relief package allocation to the affected villages, and the government authorities and other institutions may be benefitted in their

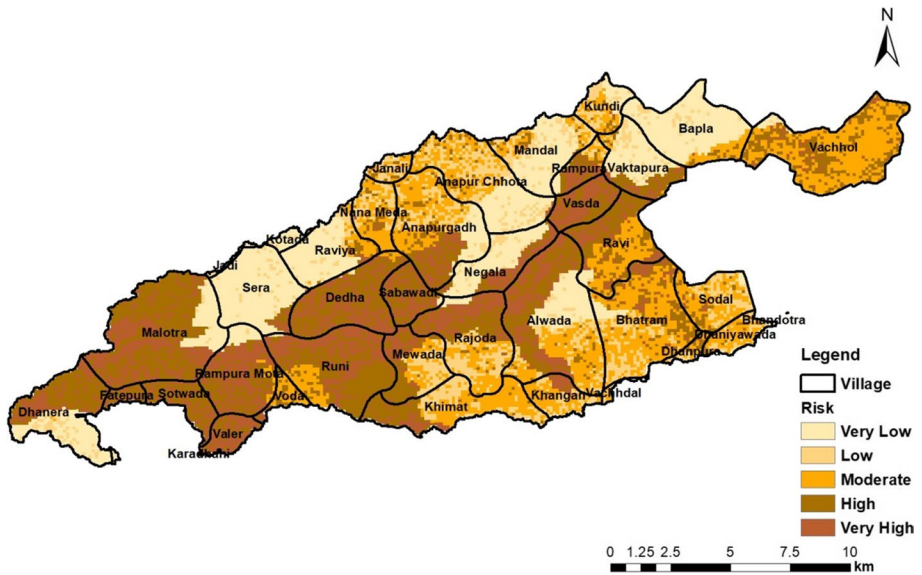


Fig. 13 Villages under risk map

decision-making. It may not only be beneficial to the organizations but also will help the hydrologists and other researchers working on hydrology and hydrodynamic modeling and may be useful to monitor disaster management systems and can serve multiple other purposes based on one's interest.

5 Recommendations

The present study is the first case in Gujarat where the semi-arid region was affected by the catastrophic flood. Cited are the suggestions and recommendations to improve the flood preparedness for any devastation flood in the future.

1. FRP prepared in this research will be validated using the field photographs, the grant should be allocated based on the proposed research, and it should justify the allocation mechanisms and reduce the extortion and corruptions prevail in the allocation of devoted money for relief and rehabilitation purpose.
2. Rainfall runoff and hydrodynamic model will be developed for Rel River basin to prepare the detail flood forecasting, flood warning and emergency action plan (EAP) as per the guidelines of Disaster management and Dam Rehabilitation and Improvement Project (DRIP).
3. The watersheds less susceptible to flood vulnerability may be useful to develop shelter places for human lives, animals and other amenities during the emergency. It will be the places where flood water could not be reached and hence operate the rescue process safely.
4. The upstream of Rel River should be developed using the appropriate soil and water conservation techniques, check dam and farm ponds should be located in appropriate

locations which can be used to store the water and reduce the runoff and soil erosion in the catchment area.

5. It was observed that the river course is very shallow and is not capable of holding the water during flooding; it would be permitted to excavate the sand from the river bed on free charges which in result will deepen the flood bed and hold the more water during a flood.
6. The site is lack of the river and rain gauges; it is a prime requirement to establish the automatic river and rain gauges to reduce the data deficiency for hydrologic, hydraulic or hydrodynamic modeling. A proper study should be executed for appropriate locations.
7. Land use and land cover, river course changes should be surveyed after the flood using the UAV and satellite techniques. Proper land use classification techniques should be developed. One can perform SWAT analysis (Kumar et al. 2018b) over different years to check the actual impact of each land use/land cover class on each basin and then can allocate low risk to high-risk categories for each LU/LC parameter. SWAT may serve as a more reliable basis for significant impact of each LU/LC class in a basin and thus may be helpful to reduce the risk of uncertainty due to LU/LC parameters up to certain extent.
8. The entire approach is developed under the scarcity of data; in future, proper field execution, testing and survey need to perform to reduce the weights parameter uncertainty in AHP method; at present, weights are assigned based on expert opinion.
9. Flood inundation mapping, flood depth, velocity of flow and arrival time in floodplain area are not considered for FRP preparation; in future, high-resolution DEM, hydrodynamic modeling and advance satellite techniques need to explore in this region to quantify the category of flood vulnerability and reduce the modeling uncertainty for decision-making system.

6 Conclusion

Flood relief package (FRP) allocation in the flood-susceptible area is a complicated decision-making process. A proper mechanism is required with the decision maker to justify a natural role in the allocation process, which satisfies the need of common people. The present case describes the integrated framework in flood relief package allocation in a developing country. The RS and GIS techniques along with the morphometric analysis, weight sum analysis, correlation matrix and AHP prove to be the robust tool for preparation of flood variability, flood risk, flood hazard map at micro-watershed level and hence are applicable for FRP allocation. As per the results, it is observed that the MWS 47, 44, 20, 23, 39, 16, 48, 52, 28 are under a very high flood hazard category and required immediate attention. Furthermore, flood hazard maps at micro-watershed level overlaid with the village information and identified Dhanera, Fatepura, Malotra, Sotwada, Valer, Rampura Mota, Runi, Dedha, Sabawadi, Ravi, Vasda, Rampura fall under high- to very high-risk category. These villages are required an immediate flood insurance and flood relief package to conferred against the flash flood of 2017. Government authority and NGOs will get help from the present work to make better management of the study area with respect to the flooding situation. This study also helps to plan rainwater harvesting, soil conservation and watershed management in the flash flood alert zones. This can be extremely beneficial to monitor basin's response during a flood event and thus may help in taking safety measures

for the areas highly susceptible to flood risk and hence help further to enhance the existing disaster management system. The study indicates that the methodology is useful and cost-effective for the regions where financial resources and labor are limited. This type of new approach would be applicable for relief package allocation for any natural hazards.

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Compliance with ethical standards

Conflict of interest The corresponding author is thankful to the ORSP, PDPU and SAC-ISRO for providing the research grant to executing the work (Grant no: ORSP/R&D/SRP/2019/MPDP/007; SAC/EPESA/GHCAG/LHD/SARITA/01/19).

References

- Abdelkareem M (2017) Targeting flash flood potential areas using remotely sensed data and GIS techniques. *Nat Hazards* 85:19–37
- Agarwal A, Narayan S (1991) State of India's environment: floods. Center for Science and Environment, New Delhi
- Aher P, Adinarayana J, Gorantiwar S (2014) Quantification of morphometric characterization and prioritization for management planning in semi-arid tropics of India: a remote sensing and GIS approach. *J Hydrol* 511:850–860
- Aksoy H, Kirca VSO, Burgan HI, Kellecioglu D (2016) Hydrological and hydraulic models for determination of flood-prone and flood inundation areas. *Proc Int Assoc Hydrol Sci* 373:137–141
- Alexander G (1972) Effect of catchment area on flood magnitude. *J Hydrol* 16:225–240
- Altaf F, Meraj G, Romshoo SA (2013) Morphometric analysis to infer hydrological behaviour of Lidder watershed, Western Himalaya, India. *Geogr J*. <https://doi.org/10.1155/2013/178021>
- Angillieri MYE (2008) Morphometric analysis of Colanguil river basin and flash flood hazard, San Juan. *Argent Environ Geol* 55:107–111
- Astaras TA, Soulakellis N (1992) Contribution of digital image analysis techniques on Landsat-5 TM imageries for drainage network delineation. A case study from the Olympus Mountain, W. Macedonia, Greece. In: Proceedings 18th annual conference of the remote sensing society, Dundee, pp 153–172
- Bajabaa S, Masoud M, Al-Amri N (2014) Flash flood hazard mapping based on quantitative hydrology, geomorphology and GIS techniques (case study of Wadi Al Lith, Saudi Arabia). *Arab J Geosci* 7:2469–2481
- Bhatt S, Ahmed S (2014) Morphometric analysis to determine floods in the Upper Krishna basin using Cartosat DEM. *Geocarto Int* 29:878–894
- CEOS (2003) The use of earth observing satellites for hazard support: assessments and scenarios. Final report of the CEOS disaster management support group (DMSG), November
- Chen Y-R, Yeh C-H, Yu B (2011) Integrated application of the analytic hierarchy process and the geographic information system for flood risk assessment and flood plain management in Taiwan. *Nat Hazards* 59:1261–1276
- Chopra R, Dhiman RD, Sharma P (2005) Morphometric analysis of sub-watersheds in Gurdaspur district, Punjab using remote sensing and GIS techniques. *J Indian Soci Remote Sens* 33:531
- Chorley RJ (ed) (1969) Introduction to fluvial processes. Methuen and Co., Ltd., London
- Choudhari P, Nigam GK, Singh SK, Thakur S (2018) Morphometric based prioritization of watershed for groundwater potential of Mula river basin, Maharashtra, India. *Geol Ecol Landsc* 2:256–267

- Chowdary V, Ramakrishnan D, Srivastava Y, Chandran V, Jeyaram A (2009) Integrated water resource development plan for sustainable management of Mayurakshi watershed, India using remote sensing and GIS. *Water Resour Manag* 23:1581–1602
- Chowdary V, Chakraborty D, Jeyaram A, Murthy YK, Sharma J, Dadhwal V (2013) Multi-criteria decision making approach for watershed prioritization using analytic hierarchy process technique and GIS. *Water Resour Manag* 27:3555–3571
- De Vaumas É (1961) Structure et Morphologie du Proche-Orient. *Nouvel essai de synthèse et orientations de recherche (1er article)*. *Revue de géographie alpine* 49:225–274
- Edet A, Okereke C, Teme S, Esu E (1998) Application of remote-sensing data to groundwater exploration: a case study of the Cross River State, southeastern Nigeria. *Hydrogeol J* 6:394–404
- Emmanouloudis D, Myronidis D, Ioannou K (2008) Assessment of flood risk in Thasos Island with the combined use of multicriteria analysis AHP and geographical information system. *Innov Appl Info Agric Environ* 2:103–115
- Eze EB, Efiog J (2010) Morphometric parameters of the Calabar river basin: Implication for hydrologic processes. *J Geogr Geol* 2:18
- Faniran A (1968) The index of drainage intensity—a provisional new drainage factor. *Aust J Sci* 31:328–330
- Fernández D, Lutz M (2010) Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. *Eng Geol* 111:90–98
- Franci F, Bitelli G, Mandanici E, Hadjimitsis D, Agapiou A (2016) Satellite remote sensing and GIS-based multi-criteria analysis for flood hazard mapping. *Nat Hazards* 83:31–51
- Gregory KJ, Walling DE (1973) Drainage basin form and process
- Guzzetti F, Tonelli G (2004) Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. *Nat Hazards Earth Syst Sci* 4:213–232
- He Y, Xie H, Cui P, Wei F, Zhong D, Gardner J (2003) GIS-based hazard mapping and zonation of debris flows in Xiaojiang Basin, southwestern China. *Environ Geol* 45:286–293
- Horton RE (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geol Soc Am Bull* 56:275–370
- Jain V, Sinha R (2003) Evaluation of geomorphic control on flood hazard through geomorphic instantaneous unit hydrograph. *Curr Sci* 85:1596–1600
- Javed A, Khanday MY, Ahmed R (2009) Prioritization of sub-watersheds based on morphometric and land use analysis using remote sensing and GIS techniques. *J Indian Soc Remote Sens* 37:261–274
- Javed A, Khanday MY, Rais S (2011) Watershed prioritization using morphometric and land use/land cover parameters: a remote sensing and GIS based approach. *J Geol Soc India* 78:63–75
- Jonkman S, Vrijling J (2008) Loss of life due to floods. *J Flood Risk Manag* 1:43–56
- Kumar Pradhan R, Srivastava PK, Maurya S, Kumar Singh S, Patel DP (2018) Integrated framework for soil and water conservation in Kosi River Basin. *Geocarto Int*. <https://doi.org/10.1080/10106049.2018.1520921>
- Kumar R, Kumar S, Lohani A, Nema R, Singh R (2000) Evaluation of geomorphological characteristics of a catchment using GIS. *GIs India* 9:13–17
- Kumar N, Singh SK, Pandey H (2018a) Drainage morphometric analysis using open access earth observation datasets in a drought-affected part of Bundelkhand, India. *Appl Geomat* 10:173–189
- Kumar N, Singh SK, Singh VG, Dzwairo B (2018b) Investigation of impacts of land use/land cover change on water availability of Tons River Basin, Madhya Pradesh, India. *Model Earth Syst Environ* 4:295–310
- Lin Y-P, Verburg PH, Chang C-R, Chen H-Y, Chen M-H (2009) Developing and comparing optimal and empirical land-use models for the development of an urbanized watershed forest in Taiwan. *Landsc Urban Plan* 92:242–254
- Malik A, Kumar A, Kandpal H (2019) Morphometric analysis and prioritization of sub-watersheds in a hilly watershed using weighted sum approach. *Arab J Geosci* 12:118
- Maurya S, Srivastava PK, Gupta M, Islam T, Han D (2016) Integrating soil hydraulic parameter and microwave precipitation with morphometric analysis for watershed prioritization. *Water Resour Manag* 30:5385–5405
- Merzi N, Aktas MT (2000) Geographic information systems (GIS) for the determination of inundation maps of Lake Mogan, Turkey. *Water Int* 25:474–480
- Meyer V, Scheuer S, Haase D (2009) A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany. *Nat Hazards* 48:17–39
- Miller VC (1953) Quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee Technical report (Columbia University Department of Geology); no 3

- Molina-Navarro E, Trolle D, Martínez-Pérez S, Sastre-Merlín A, Jeppesen E (2014) Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. *J Hydrol* 509:354–366
- Montgomery DR, Dietrich WE (1989) Source areas, drainage density, and channel initiation. *Water Resour Res* 25:1907–1918
- Montgomery DR, Dietrich WE (1992) Channel initiation and the problem of landscape scale. *Science* 255:826–830
- Ozdemir H, Bird D (2009) Evaluation of morphometric parameters of drainage networks derived from topographic maps and DEM in point of floods. *Environ Geol* 56:1405–1415
- Pallard B, Castellarin A, Montanari A (2009) A look at the links between drainage density and flood statistics. *Hydrol Earth Syst Sci* 13:1019–1029
- Patel DP, Dholakia MB, Naresh N, Srivastava PK (2012) Water harvesting structure positioning by using geo-visualization concept and prioritization of mini-watersheds through morphometric analysis in the Lower Tapi Basin. *J Indian Soc Remote Sens* 40:299–312
- Patel DP, Srivastava PK, Gupta M, Nandhakumar N (2015) Decision Support System integrated with Geographic Information System to target restoration actions in watersheds of arid environment: a case study of Hathmati watershed, Sabarkantha district, Gujarat. *J Earth Syst Sci* 124:71–86
- Patton PC, Baker VR (1976) Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. *Water Resour Res* 12:941–952
- Pidwirny M (2008) Stream morphometry. In: Cleveland CJ, editor, Draggan S, Topic editor. *Encyclopedia of Earth*. Washington (DC): Environmental Information Coalition (EIC) of the National Council for Science and the Environment (NCSE). Available from: http://www.eoearth.org/article/Stream_morphometry
- Ratnam KN, Srivastava Y, Rao VV, Amminedu E, Murthy KSR (2005) Check dam positioning by prioritization of micro-watersheds using SYI model and morphometric analysis—remote sensing and GIS perspective. *J Indian Soc Remote Sens* 33:25–38
- Reddy GPO, Maji AK, Gajbhiye KS (2004) Drainage morphometry and its influence on landform characteristics in a basaltic terrain, Central India—a remote sensing and GIS approach. *Int J Appl Earth Obs Geoinf* 6:1–16
- Romshoo SA, Bhat SA, Rashid I (2012) Geoinformatics for assessing the morphometric control on hydrological response at watershed scale in the Upper Indus Basin. *J Earth Syst Sci* 121:659–686
- Roughani M, Ghafouri M, Tabatabaei M (2007) An innovative methodology for the prioritization of sub-catchments for flood control. *Int J Appl Earth Obs Geoinf* 9:79–87
- Saaty TL, Vargas LG (1980) Hierarchical analysis of behavior in competition: prediction in chess. *Syst Res Behav Sci* 25:180–191
- Sanyal J, Lu XX (2006) GIS-based flood hazard mapping at different administrative scales: a case study in Gangetic West Bengal, India. *Singap J Trop Geogr* 27:207–220
- Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geol Soc Am Bull* 67:597–646
- Shaban A, Khawlie M, Abdallah C, Awad M (2005) Hydrological and watershed characteristics of the El-Kabir River, North Lebanon. *Lakes Reserv Res Manag* 10:93–101
- Sharma R, Sahai B, Karale R (1986) Identification of erosion-prone areas in a part of the Ukai catchment. In: Asian conference on remote sensing, 6 th, Hyderabad, India, pp 121–126
- Singh O, Kumar D (2018) Evaluating the influence of watershed characteristics on flood vulnerability of Markanda River basin in north-west India. *Nat Hazards* 96:1–22
- Sinha R, Bapalu GV, Singh LK, Rath B (2008) Flood risk analysis in the Kosi river basin, north Bihar using multi-parametric approach of analytical hierarchy process (AHP). *J Indian Soc Remote Sens* 36(4):335–349
- Smith KG (1950) Standards for grading texture of erosional topography. *Am J Sci* 248:655–668
- Sreedevi P, Owais S, Khan H, Ahmed S (2009) Morphometric analysis of a watershed of South India using SRTM data and GIS. *J Geol Soc India* 73:543–552
- Stefanidis S, Stathis D (2013) Assessment of flood hazard based on natural and anthropogenic factors using analytic hierarchy process (AHP). *Nat Hazards* 68:569–585
- Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. In: Chow VT (ed) *Handbook of Applied Hydrology*. McGraw Hill, New York, pp 40–74
- Sui D, Maggio R (1999) Integrating GIS with hydrological modeling: practices, problems, and prospects. *Comput Environ Urban Syst* 23:33–51
- Syed NH, Rehman AA, Hussain D, Ishaq S, Khan AA (2017) Morphometric analysis to prioritize sub-watershed for flood risk assessment in Central Karakoram National Park using GIS/RS approach. *ISPRS Ann Photogramm Remote Sens Spat Inf Sci* 4:367

- Taha MM, Elbarbary SM, Naguib DM, El-Shamy I (2017) Flash flood hazard zonation based on basin morphometry using remote sensing and GIS techniques: a case study of Wadi Qena basin, Eastern Desert, Egypt. *Remote Sens Appl Soc Environ* 8:157–167
- Tucker GE, Bras RL (1998) Hillslope processes, drainage density, and landscape morphology. *Water Resour Res* 34:2751–2764
- Verstappen HT (1983) Applied geomorphology: geomorphological surveys for environmental development (No. 551.4 VER)
- Waikar M, Nilawar AP (2014) Morphometric analysis of a drainage basin using geographical information system: a case study. *Int J Multidiscipl Curr Res* 2:179–184
- Yadav SK, Singh SK, Gupta M, Srivastava PK (2014) Morphometric analysis of Upper Tons basin from Northern Foreland of Peninsular India using CARTOSAT satellite and GIS. *Geocarto Int* 29:895–914
- Yildiz O (2004) An investigation of the effect of drainage density on hydrologic response. *Turk J Eng Environ Sci* 28:85–94
- Youssef AM, Pradhan B, Hassan AM (2011) Flash flood risk estimation along the St. Katherine road, southern Sinai, Egypt using GIS based morphometry and satellite imagery. *Environ Earth Sci* 62:611–623

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