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Flash Flood Risk Susceptibility in Gagas River Watershed - Kumaun Lesser Himalaya

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Abstract Himalayan region is highly susceptible to natural hazards particularly those that are triggered by the action of water. Due to the vast topographical diversity, events of 'peak runoff' pose various risks to small villages located at the watershed's foot area. In this study, for the purpose to estimate flash flood risk along the Gagas River in Kumaun lesser Himalaya, high-resolution Digital Elevation Model (DEM) coupled with Geographical Information Systems (GIS) were utilised. The region experiences frequent storm events especially in the monsoon season. The river basin is also an evolving HELP basin endorsed by UNESCO as part of its global efforts for restoration of languishing river systems. Variability in the climatic conditions has imposed undue pressure on the livelihoods for survival. Relevant morphometric, topographic parameters and maximum runoff of the sub-watersheds of Gagas river watershed were computed in the GIS environment and were analysed to understand the drainage basins susceptibility to the flash flood hazards. These measurements allowed prioritising the sub watersheds in the presence of a series of rainstorms that generate unusual runoff volumes. Map representing hazard zones of sub-watersheds were identified and classified into four susceptibility groups (very high, high, moderate and low). The knowledge of flash flood susceptibility is important in mitigating the losses incurred to agriculture, irrigation systems, watermills, and recreational activities; and in the proper management of water resources.
Keywords *Morphometry; Flash Floods; Himalaya; Prioritisation*

1. Introduction

In complex mountainous environment such as Himalayas, due to their high susceptibility to natural hazards such as debris flows, debris floods, and flash floods, hydric analysis is very important, so that appropriate risk management could be initiated. The unprecedented rate of Climate Change causing increase in high intensity rainfall and decrease in low and medium intensity events renders the situation more vulnerable to the after effects (Goswami et al., 2006; ICIMOD, 2007).

Flows hastened by intense rainfalls are often referred to as ''flash floods'', these, according to IAHS-UNESCO WMO (1974) are defined as sudden floods with high peak discharges, produced by severe thunderstorms that are generally of limited areal extent. However, the actual time threshold may vary depending on particular hydrological characteristics such as small basins; steep slopes in the catchment, low infiltration capacity combined with meteorological events (Georgakakos, 1986).

In the Himalayas, this is a frequent phenomenon, especially the peak discharge in the monsoon season, with very severe implication to life and infrastructure developments and shall require appropriate adaptation measures to be taken up (Sharma, 2012). Management of flood occurrences requires information about both climatic conditions (i.e. rainfall, temperature, storm occurrences) and a watershed’s physiographic characteristics (i.e. slope, elevation, drainage density etc.). Various morphometrical parameters including linear, areal and relief aspects are used worldwide for the characterisation of fluvial originated drainage basin (Chalam et al., 1996) and due to its perspective view Remote Sensing (RS) and Geographical Information System (GIS) applications has been useful for monitoring and management of watersheds. It outplays conventional studies since these techniques coupled with high-resolution Digital Elevation Model (DEM) measure a number of terrain and morphometric parameters efficiently, precisely and rapidly to characterise the stream network and watersheds (Vijith and Satheesh, 2006).

In order to study this approach in a hilly watersheds with steep overland, stream slopes and areas inclined to the flood phenomena, this study was undertaken in the Gagas Watershed, a hilly sub-watershed of the Ramganga River Basin, in the Kumaun Lesser Himalaya. The region experiences frequent storm events almost every year in the monsoon season (June 4, 1977; June 25, 1978; June 20, 1981; July 31, 1982; August 11, 1983; August 31, 1984; August 10, 1985; August 15, 1985) (Kumar and Kumar, 2008). Due to its high dependence on the River system, the basin has been endorsed by HELP (Hydrology for Environment, Life and Policy), under UNESCO’s International Hydrological Program as part of its global efforts for restoration of languishing river systems (www.unesco.org/water/ihp/help/). In this paper, stream properties, basin characteristics and maximum stream discharge of the Gagas watershed and its sub watersheds have been analysed for their risk of flash floods and for prioritisation.

2. Study Area

The Gagas watershed covers an area of 511.19 Km^2 having perimeter 129.59 Km. It is the largest tributary basin of the Himalayan Ramganga River in the South-Western portion of Almora district of Uttarakhand, India, extending from 29°51'55" N and 29°35'49" N and longitudes 79°20'36" E and 79°33'15" E (Figure 1). The topography of the region varies from 2742 m amsl in the head reaches of the Gagas River in the North-Eastern part to 727 m amsl at the mouth of the Gagas River in the western part of the basin. The river originates in the sacred forests of Pandukholi in Almora district of the Kumaun lesser Himalaya.

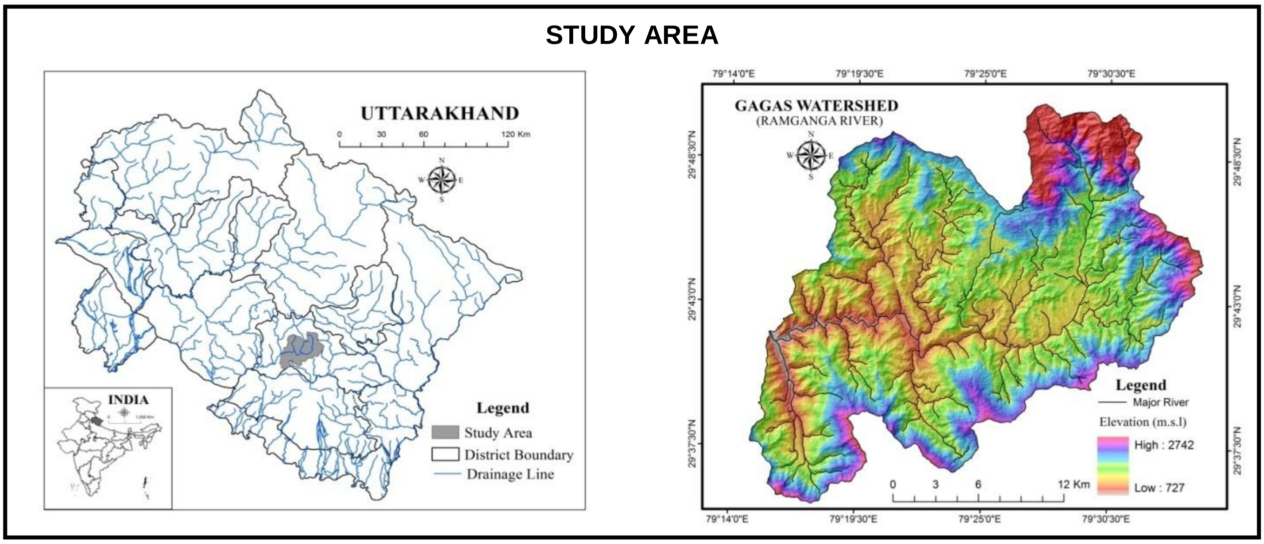

Figure 1: *Study Area of Gagas Watershed*

The study area lies in the Dudhatoli syncline range and constitutes a variety of meta-sediments like slate, phyllite, quartzite, mica-schist, gneiss, granite etc. that have suffered multiple phases of deformation and metamorphism (Pal, 2002). The area is dissected by major thrusts (North Almora, South Almora, Ramgarh) along the boundaries of major rock groups (Figure 2). The North Almora Thrust (NAT) is dissected by faults, which are transverse to the Himalayan orographic trend and are known as seismically active structures (Paul and Pant, 2003). The watershed is characterised by coarse textured soils and a number of tributaries spread the entire watershed having dendritic pattern. Morphologically the region is characterized by a series of deeply incised river valleys and high ridges (Kharkwal, 1993).

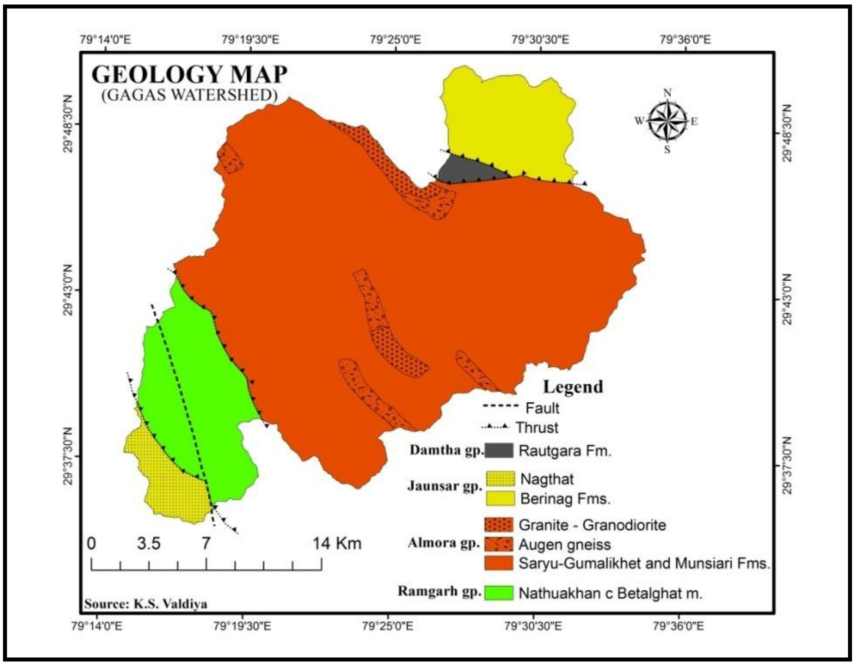

Figure 2: *Geology Map of the Study Area*
(Source: K.S. Valdiya, 1980)

In the watershed, the mean annual rainfall varies from 903 to 1,281 mm, with a mean value of 1,067 mm (Kumar and Kumar, 2008). Approximately, more than 80% of the annual precipitation in the region occurs during the South-West monsoon, which starts in the third week of June and can last till mid-October. Of the remaining, 15% rainfall is caused by cyclones and 5% by local thunderstorms distributed over the rest of the year (Jalal, 1988). Since, in the mountains, the topography has a major role in affecting the orographic precipitation, which varies significantly over small spatial scales (Shrestha et al., 2012). The phenomenon is resurrected by using the high resolution Bioclim data; it is observed that in the Gagas watershed the distribution of rainfall is effected by altitude variations, slope, aspect, and trends of mountain ranges. Duration of 50 years (1950-2000) of climatic data is classified into three seasons. The maximum average rainfall was observed in July (449.6 mm). Seasonal distribution of rainfall and temperature is represented with the maps (Figure 3), and monthly variations of the climatic data are shown with a hyetograph along with temperature isotherms (Figure 4).

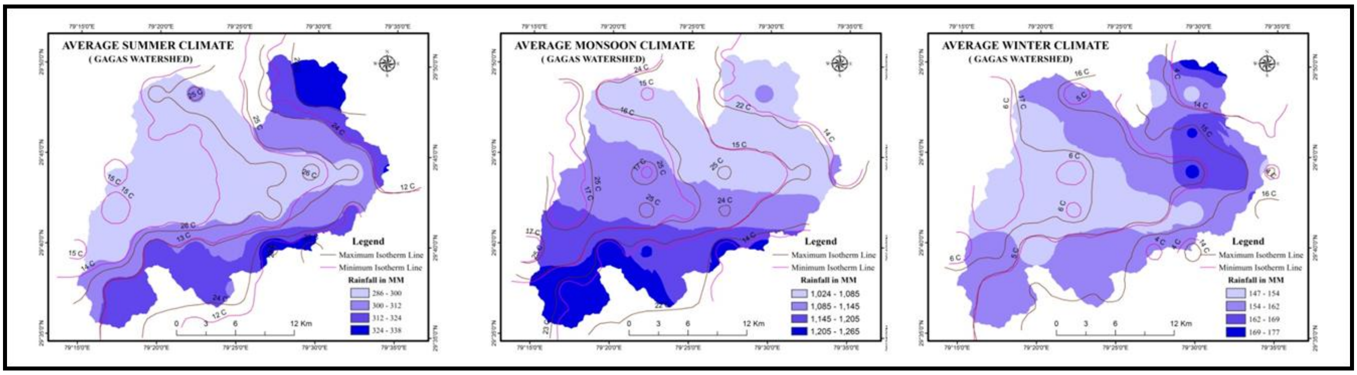

Figure 3: *Seasonal Climatic Maps of Gagas Watershed (1950-2000)*
(Source: www.worldclim.org)

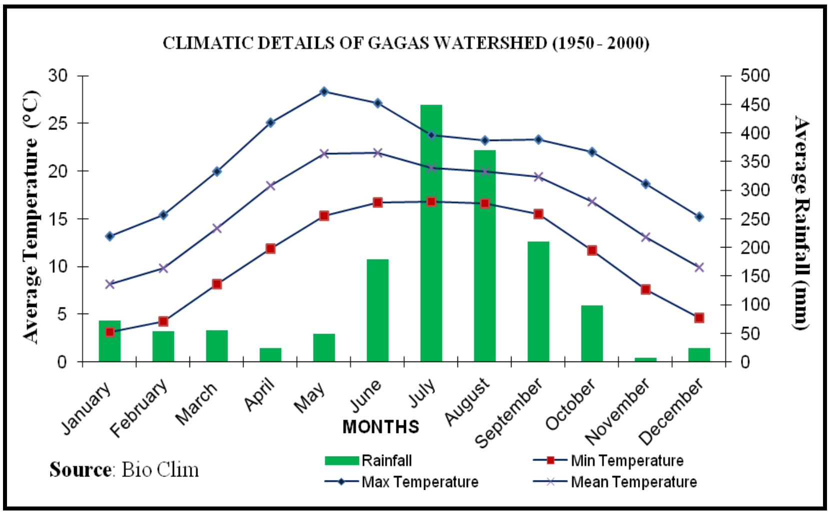

Figure 4: *Average Monthly Profile of Gagas Watershed (1950-2000)*
(Source: www.worldclim.org)

3. Data Used and Methodology

The present study includes following approaches (1) Survey of India (SOI) topographic maps (No. - 530/5, 530/6, 530/9, 530/10) of 1958 (1:50,000 scales) to outline the natural drainage (2) ASTER data, with 30 m spatial resolution for DEM generation (Figure 5).

Strahler's scheme for stream ordering was used to digitize the drainage, by the use of toposheets on 1:50000 scale and were updated using remote sensed data (Landsat 8, Feb 2015). In the study, along with perennial streams, ephemeral streams were also digitised as a geomorphic agent during flash floods (Moges and Bhole, 2015). A 30 m resolution ASTER DEM was used to delineate the Gagas River watershed, subwatersheds and to extract altitude and slope layers using Arc Map and Arc Hydro tools. Table 1 describes the standard methods and formulae used for calculating the morphometric parameters in the 13 sub watersheds of the Gagas basin and the results are given in Tables 2, 3, 4.

Table 1: *Definitions and Formulae of Morphometrical Parameters, Slope Categories, Wetness Index and Maximum Discharge used for the Analysis*

S. No.	Parameters	Definitions	Units	References
		Drainage Network Characteristics		
1	Total number of streams (Nu)	The number of stream segments of various orders in a sub-watershed.	Dimensionless	Strahler (1957)
2	Stream orders (u)	Hierarchial ordering	Dimensionless	Strahler (1957)
3	Stream length (Lu)	Length of the stream orders.	Km	Horton (1945)
4	Total stream length	The lengths of total number of stream segments of various orders in a sub-watershed	Km	Horton (1945)
5	Longest flow path (Ls)	Length of main stream.	Km	
5	Stream grade (Sg)	(Hs-Hd)/Ls *100	%	Hack (1957)
6	Bifurcation ratio (Rb)	Nu/N(u+1), where Nu is number of streams of any given order and N (u+1) is number in the next higher order	Dimensionless	Horton (1945)
7	Weighted mean bifurcation ratio (WRbm)	Total of Rb*(Nur)/Total of(Nu-r); Nur=Number of stream used in the ratio	Dimensionless	Strahler (1953)
8	Drainage texture (Dt)	Total no. of stream segments in all order/ P	Km^{-1}	Horton (1945)
9	Drainage density (D)	∑Lt/A, where ∑Lt is the total length of all the ordered streams	$Km\ Km^{-2}$	Horton (1945)
10	Length of overland flow (Lg)	1/2Dd	Km	Horton (1945)
		Basin Geometry		
11	Basin area (A)	Area of watershed	Km^2	
12	Basin length (Lb)	Maximum length of the watershed measured parallel to the main drainage line.	Km	Schumm (1956)
13	Perimeter (P)	Length of the watershed boundary	Km	
14	Perimeter of circle of watershed (Pc)	2πr	Km	
15	Form factor (Rf)	A/Lb^2	Dimensionless	Horton (1945)
16	Elongation ratio (Re)	$\sqrt{(A/\pi)}/Lb$	Dimensionless	Schumm (1956)
17	Circulatory ratio (Rc)	$4\pi A/P^2$	Dimensionless	Miller (1953)
18	Compactness coefficient (Cc)	Perimeter/ Perimeter of Circle of Watershed	Dimensionless	Gravelius (1914)
		Relief Characteristics		
19	Relative relief (Rr)	Basin Relief/Perimeter*100	Dimensionless	Huggett and Cheesman (2002)
		Slope Aspects		
20	Slope categories	Different slope categories	Degree	NRCC (1998)
		Wetness Index (WI)		
21	Wetness Index (WI)	ln (A/ tan ß); where, A is the upslope contributing area per unit contour length (	Dimensionless	Digital Terrain Analysis Manual,

		a/c) and tan ß is the local slope		University of Minnesota (2013)
		Stream Flow		
22	Maximum Discharge (Q)	$Q = C.A^{0.75}$, where C = 2.342 log (0.6T) log (1185/P) + 4 and P= 100 (6) / A	m^3/s	Punmia et al., 2009; Dawdy et al., 2012;Rijal 2014

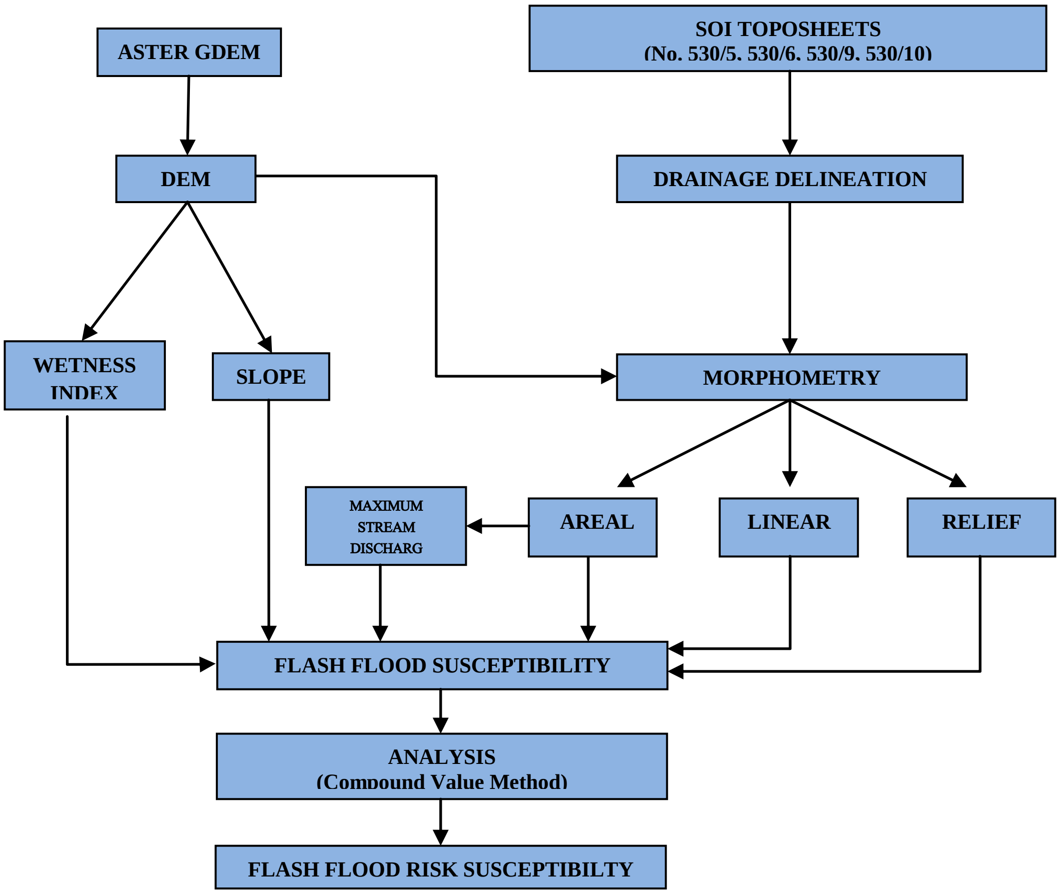

Figure 5: *Flow Chart of Steps in Analysis for Evaluating Flashflood Susceptibility of Gagas Sub Watersheds*

For the slope analysis, a standard slope classification is adopted to establish the relation between slopes and flash floods using Surface Analysis Tool in ArcGIS-9.3 (NRCC, 1998). The areas of sub watersheds were categorized into the following 10 slope classes: level (0°–0.3°), nearly level (0.3°–1.1°), very gentle slope (1.1°–3.0°), gentle slope (3.0°–5.0°), moderate slope (5.0°–8.5°), strong slope (8.5°–16.5°), very strong slope (16.5°–24°), extreme slope (24°–35°), steep slope (35°–45°), and very steep slope (45°–90°). For the purpose of analysis of its impact on surface runoff, ranking were given on the basis of percent area in the specific slope class, assuming that runoff in a particular slope class remains same in the sub watersheds.

In the study as an important parameter secondary topographic factor, wetness index (WI), has been applied for the flash flood susceptibility in the region. It considers catchment area and slope gradient and controls the flow accumulation in a terrain (Qin et al., 2011). It is helpful to delineate water saturation zone and determine water table conditions, and is calculated using the following formula:

$$TWI = \ln (A / \tan ß) \qquad (1) \qquad \text{(Anon., 2013)}$$

Where, A is the upslope contributing area per unit contour length (a/c) and tan ß is the local slope.

A regional analysis of stream flows is performed that is based on relation between discharges to drainage area (Dawdy et al. 2012). Modified Dicken's Method was used to calculate maximum discharge for the region:

$$Qmax = CA^{0.75} \qquad (2) \qquad \text{(Rijal, 2014; Punmia et al., 2009)}$$

Where, Qmax = maximum discharge (m^3/sec); A = drainage area (Km^2); and C = coefficient related to the region.

Wherein C is calculated using the formula:

$$C = 2.342 \log (0.6T) \log (1185/P) + 4 \qquad (3)$$

And

$$P= 100 (6) / A \qquad (4) \qquad \text{(Rijal, 2014)}$$

Here, A is the total catchment area (Km^2) respectively and T is return period in years (i.e. yearly).

For assessing the combined role of morphometrical and topographical parameters on the hydrological behaviour at sub watershed scale, a comparative runoff ranking methodology has been used. A compound value (Cp) was given to the parameters of sub watersheds to analyze the flash flood discharge susceptibility. This approach is based on the principles of knowledge-driven modeling and converts the qualitative understanding of a phenomenon based on scientific knowledge into a quantitative estimation. This method is one of the best approaches to compare land surface processes between similar entities (such as watersheds) (Ratnam et al., 2005).

In the study area, the total number of ranks assigned is based on the number of watersheds. Since there are 13 sub-watersheds, ranks were assigned from 1 to 13. For the purpose of analysis, rank 1 was assigned in a way that the value of the parameter represents maximum run off potential and vice versa. Same values of the parameters were assigned with similar rankings. The average of the ranks represents the collective impact of all the parameters on run off susceptibility of a sub-watershed. It is denoted as Cp and is calculated from following formula.

$$Cp = \sum R / n \qquad (5)$$

Wherein,

Cp is Compound value of a particular watershed, R is Rank of a particular sub watershed for a parameter, n is Number of parameters.

Comparison of Different Parameters for Prioritizing Flash flood Susceptibility

In the ranking, the factors such as weighted mean bifurcation ratio (Rbm), drainage texture (Dt), drainage density (D), length of overland flow (Lg), shape factors (form factor (Rf), elongation ratio (Re), circulatory ratio (Rc), compactness coefficient (Cc)), and relative relief (Rr), slope categories having a major role in the flash flood formation are calculated. Other important parameters such as stream grade, watershed area or the size, wetness index and empirical maximum stream discharge are derived using RS/GIS techniques, these have not been utilised for such studies till now in the Uttarakhand Himalayan region.

4. Results and Discussion

In the Gagas watershed, the drainage patterns is dendritic, indicating uniformly dipping bedrock, those are impervious and non-porous (Lambert, 1998). It also indicates less percolation and maximum runoff especially in the high areas. Table 2 represents the basic morphometric characteristics of the Gagas watershed. In the watershed, there are a total number of 3240 streams of total length of 1790.11 Km.

Table 2: *Basic Watershed Characteristics of the Study Area*

Linear Parameters								Areal Parameters			
		Rb									
Nu	Lu (Km)	I/II	II/III	III/IV	IV/V	V/VI	Rbm	A (Km^2)	Lb (Km)	P (Km)	Pc (Km)
3240	1790.11	4.3	4.4	4.7	2.5	5.5	4	511.19	24.31	129.59	80.13

Stream Number (Nu), Stream length (Lu), Bifurcation ratio (Rb) Mean bifurcation ratio (Rbm), Basin area (A), Basin length (Lb), Perimeter (P), Perimeter of circle of watershed (Pc)

4.1. Morphometric Analysis

Morphometry has a substantial affect on the watershed hydrology viz. the basin area determines the amount of water yield; the length, shape and relief, affect the rate at which water is discharged from the basin (Tucker and Bras, 1998) (Table 3).

Table 3: *Quantitative Morphometry Parameters used in Ranking of Gagas Sub Watersheds*

	Drainage Network and Texture							Basin Geometry			
Sub-Watersheds	**Order of Tributaries**	**Sg (%)**	**WRbm**	**Dt (Km^{-1})**	**D (Km^{-1})**	**Lg (Km)**	**A (Km^2)**	**Rf**	**Re**	**Rc**	**Cc**
Bainali	5	7.52	4.74	6.63	3.71	0.135	16.53	0.34	0.33	0.56	1.34
Bhikiyasen	3	10.41	5.89	3.51	3.59	0.139	5.25	0.64	0.45	0.59	1.30
Dusad	5	5.27	4.53	5.18	3.25	0.154	26.46	0.26	0.29	0.36	1.67
Gagas Sub	5	11.7	4.61	9.35	3.76	0.133	63.05	0.48	0.39	0.43	1.53
Jamgad	5	9.94	4.07	8.68	3.66	0.136	41.13	0.67	0.46	0.58	1.32
Kali	4	15.02	3.60	4.08	3.64	0.137	6.78	0.37	0.34	0.53	1.38
Kaneri	4	13.56	3.72	4.98	3.21	0.156	15.65	0.41	0.36	0.56	1.33
Khar	6	5.49	4.04	9.22	3.41	0.147	62.14	0.4	0.36	0.55	1.35
Khirao	4	7.26	4.07	4.53	3.59	0.139	27.27	0.22	0.26	0.26	1.96
Makraon	6	13.76	3.36	6.18	3.96	0.126	13.82	0.57	0.43	0.68	1.21
Malla	5	5.88	4.41	9.13	3.33	0.150	47.49	0.52	0.41	0.57	1.32
Narora	6	10.48	4.33	12.19	3.83	0.131	59.52	0.92	0.54	0.64	1.25
Riskan	5	3.74	4.55	9.42	3.84	0.130	51.17	0.3	0.31	0.44	1.51
Total Gagas	6	4.21	4.32	25	3.5	0.143	511.19	0.86	0.52	0.38	1.62

Stream grade (Sg), Weighted mean bifurcation ratio (WRbm), Drainage texture (Dt), Drainage density (D) Length of overland flow (Lg), Basin area (A), Form factor (Rf), Elongation ratio (Re), Circulatory ratio (Rc), Compactness coefficient (Cc)

4.1.1. *Drainage Network Analysis*

The Gagas watershed was observed of having three 'sixth' order tributaries, and six 'fifth' order tributaries, three 'fourth' order tributaries and one 'third' order tributary. In the watershed more number of higher stream order tributaries shows the association with more discharge and higher velocity of the stream flow.

Stream Grade (Sg)

As an important parameter defined by slope of the channel, it influences most aspects of flood-plain geomorphic and hydrologic processes (Hack, 1957 and 1973). A high stream grade 15.02 (Kali) shows increased flow velocity leading to extensive flood damage on the high-gradient reaches than on the more gentle reaches (Hupp, 1982).

Weighted Mean Bifurcation Ratio (WRbm)

A mountainous or highly dissected terrain has a high bifurcation ratio and vice versa, which suggests that its value is related to geomorphic factors such as relief ratio, drainage density, etc. (Horton, 1945). Basins of high WRbm are elongated in shape, which in turn gives sufficient time for infiltration and ground water recharge, and low probability of flooding and vice versa (Barseem et al., 2013). According to Strahler (1953), WRbm give more representative bifurcation indexes, in the watershed it varies between 5.89 (Bhikiyasen) and 3.36 (Makraon). The sub watersheds with closer range in the variations are ascribed to the similar rock group composition and tectonic history, uniform climate conditions and in similar stage of development (Pakhmode et al., 2003).

Drainage Texture (Dt)

Drainage texture is the measure of the channel spacing and depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development of a basin. A fine texture expresses soft or weak rocks uncovered by vegetation, whereas coarse textures represent massive and resistant rocks (Dornkamp and King, 1971). Based on the classification of Smith (1950), Narora (12.19 Km^{-1}) with fine texture show lower infiltration and higher runoff; while Bhikiyasen (3.51 Km^{-1}) followed by Kali (4.08 Km^{-1}) have coarse textures, with a large basin lag time.

Drainage Density (D)

Drainage density (D) indicates how dissected the landscape is by channels and in the formation of flood flows (Horton, 1932; Gardiner and Gregory, 1982). It is higher in weak/impermeable rocks with sparse vegetation cover. It increases with increasing probability of heavy rainstorms, rapid storm response, less infiltration and moderate erodibility of surface materials and vice versa (Betson, 1964). The values in Gagas sub watersheds varies from 3.21 (Kaneri) to 3.96 (Makaraun) $KmKm^{-2}$, with an average value of 3.6 $KmKm^{-2}$ showing high drainage density.

Length of Overland Flow (Lg)

Length of overland flow (Lg) is the length of the run of rainwater on the ground surface before it is localized into definite channels and is roughly equal to half of drainage density (Horton, 1945). If a basin is well drained the Lg is short and the surface runoff concentrates quickly. Lg in the Gagas watershed varies from 0.126 (Makraun) to 0.156 Km (Kaneri) indicating gentler slopes and longer flow paths in the latter.

4.1.2. *Basin Geometry*

Basin geometry is a means of numerically analyzing different areal aspects of a drainage basin. These parameters affect the stream flow hydrographs and peak flows of the basins.

Area (A)

Watershed's area is an important parameter like the stream lengths of the drainage. As basin enlarges, the stream length increases and there is a delay in arrival of flow after heavy rain (Hack, 1957). Basin area vary from 63.05 Km^2 (Gagas sub) to 5.25 Km^2 (Bhikiyasen). Out of the total, nine sub watersheds fall in the range of 10-50 Km^2 of area.

Watershed Shape

Basin shape is a dimensionless factor that characterises the value range from 0 (a line, highly elongated shape) to unity (a circle) (Miller, 1953). The form factor (Rf) values vary from 0.22 (Khirao) to 0.92 (Narora) which shows the variations from elongated to perfectly circular shapes, the latter being more susceptible to peak runoff of shorter duration (Chopra et al., 2005). Gagas watershed has an average Rf of 0.47. Elongation ratio (Re) varies from 0.26 (Khirao) to 0.54 (Narora). Higher value of Re indicates active denudational processes with high infiltration capacity and low run-off in the basin, whereas, lower Re values indicate higher elevation of the basin susceptible to high headward erosion along tectonic lineaments (Avinash et al., 2011). Gagas watershed has an average Re of 0.38 which indicate moderate slope. The circularity ratio (Rc) is used for the out-line form of watershed as a quantitative method (Miller, 1953). Its low, medium and high values are indicative of the youth, mature and old stages of the life cycle of the tributary basins. In the sub watersheds, the Rc ranges from 0.26 (Khirao) to 0.68 (Makraon) (Table 4).

Compactness Coefficient (Cc)

Another dimensionless parameter, the compactness coefficient is independent of size of watershed and dependent only on the slope. For a circular basin Cc=1, and a deviation from the circular nature will have values greater than 1 (Gravelius, 1914). The runoff hydrograph is expected to be sharper with a greater peak and shorter duration, in a more compacted watershed i.e. more closer to 1 (Avery, 1975). Its values range from lowest in Makraon (1.21) to highest in Khirao (1.96) sub watersheds.

In an analysis of comparison between the average values of form factor (Rf), elongation ratio (Re) and circularity ratio (Rc) with order of tributaries >3. It is observed that order of tributaries is directly proportional with these ratios i.e. with increasing order of tributaries, the tendency of sub watersheds to be more circular in shape and hence increasing vulnerability to flash floods. The compactness coefficient (Cc), however show as indirect proportional to order (Figure 6). The analysis depicts these as significant parameters in drainage-basin evolution, expressing increases in the order of the main stream, in the area and in other parameters of elongated basins in relation to circular ones.

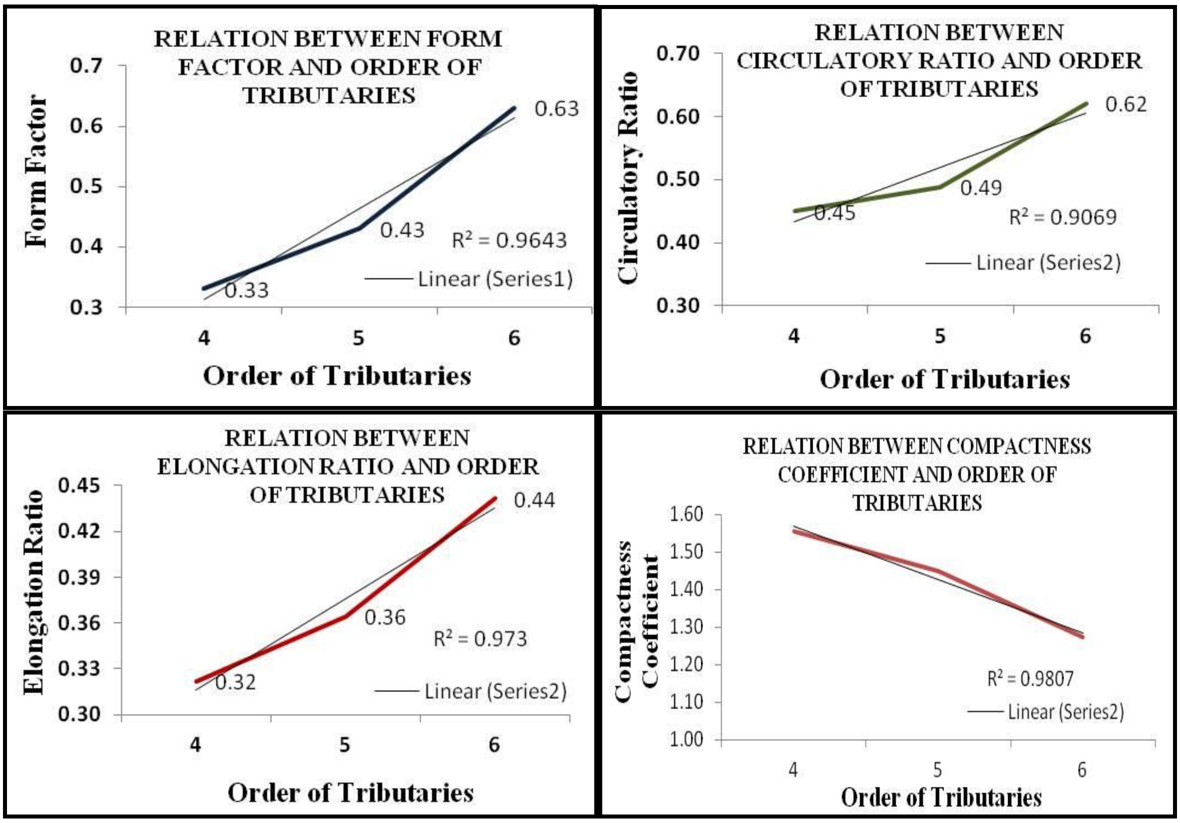

Figure 6: *Graphs Showing Relation between Different Basin Shape Parameters and Order of Tributaries.*

4.1.3. *Relief Characteristics*

Relative Relief (Rr) is an important morphometric variable used for the general estimation of morphological characteristics of terrain (Melton, 1957). The relative relief for watersheds varies from 1.97% (Riskan) to 6.60% (Kali) indicating higher runoff potential in Kali than others (Table 4).

4.2. Slope Categories and Wetness Index

In the hill slope estimation, the steep slope zones enhance the quick runoff during rains or storm events (Tucker and Bras, 1998). In the Gagas watershed, maximum 36.5% of the total area falls in slope range of 24°–35° under extreme slope category, while minimum 0.01% falls in the lowest slope category of 0°–0.3° (Table 4).

Another important parameter to quantify topographic control on hydrological processes is wetness index (WI) or topographic wetness index (TWI). Soil moisture is considered as the most important soil factor for rapid runoff and flash flooding. The higher WI empirically represents the spatial distribution of soil moisture, surface saturation and hence surface runoff which is an important factor to simulate soil erosion processes as well (Kienzel, 2004). It is expressed as the movement of water in terrain slope or local drainage by downslope topography. Sub watershed Gagas sub have been observed with highest value (11378) expressing potentially wetter region thus more runoff generation from such saturated areas, whereas Kali with the lowest value (5112) depicts a dry landscape (Table 4).

4.3. Maximum Discharge

As a function of the contributing area of a watershed, maximum flood have been derived by using the modified Dicken's method that helps in estimating the range of peak discharges in different watersheds (Dawdy et al., 2012). However these values show the highest range, the sub watershed Gagas sub (49.87 m^3/s) is most vulnerable to flash floods as compared to Bhikiyasen (8.82 m^3/s) according to the estimated values (Table 4).

Table 4: *Relief Ratio, Slope Categories, Wetness Index and Maximum Discharge used in Ranking of Gagas Sub Watersheds*

Sub-Watersheds	Relative relief (Rr)	Wetness Index (WI)	Slope (Area in %)										Maximum Discharge (Q) (m^3/s)
			0°–0.3°	0.3°–1.1°	1.1°–3.0°	3.0°–5.0°	5.0°–8.5°	8.5°–16.5°	16.5°–24°	24°–35°	35°–45°	> 45°	
Bainali	4.303	9900	0.00	0.11	0.78	1.94	4.85	18.58	28.52	38.52	6.53	0.17	19.68
Bhikiyas	5.379	8464	0.01	0.04	0.19	0.72	2.42	13.15	31.07	44.26	8.06	0.07	8.82
Dusad	2.145	10476	0.01	0.18	1.28	2.94	7.98	28.90	31.68	24.64	2.66	0.02	27.31
Gagas Sub	3.658	11378	0.01	0.35	2.28	2.83	4.90	16.98	23.41	32.82	14.19	2.23	49.87
Jamgad	3.489	10950	0.00	0.04	0.42	0.92	3.06	18.35	32.72	39.11	5.25	0.12	37.09
Kali	6.604	5112	0.01	0.02	0.48	0.97	3.28	20.59	31.90	35.28	6.97	0.49	10.56
Kaneri	5.633	9946	0.00	0.04	0.28	0.70	2.22	15.08	34.14	42.19	5.21	0.13	18.94
Khar	2.494	11345	0.01	0.13	0.82	1.73	4.70	23.52	34.49	29.67	4.62	0.32	49.37
Khirao	3.347	10281	0.02	0.23	2.04	4.77	12.68	33.48	24.20	19.29	3.27	0.12	27.88
Makrao	5.485	9851	0.01	0.12	0.78	1.60	5.24	30.40	35.39	22.67	3.55	0.24	17.37
Malla	3.105	11043	0.00	0.10	0.78	1.68	5.13	22.39	30.50	34.27	5.05	0.11	40.98
Narora	3.630	11311	0.01	0.14	0.86	1.61	4.09	17.14	30.57	37.61	7.53	0.43	47.92
Riskan	1.968	11130	0.00	0.12	0.86	1.89	5.24	23.91	33.65	30.00	4.17	0.15	43.16
Total Gagas	1.536	13462	0.01	0.17	1.15	2.08	5.25	21.56	30.43	32.46	6.38	0.51	209.83

5. Assessing Flash Flood Risk Vulnerability

Flash flood risk susceptibility assessment of the sub watersheds of Gagas watershed was performed by the summation of the runoff ranks of relevant influencing parameters i.e., morphometric (linear, areal and relief), slope, wetness index and maximum discharge (Table 5). A compound value (Cp) representing the runoff susceptibility was calculated for different watersheds accordingly. A Cp of 5–6 is categorised as with very high priority, 6–7 as high priority, 7–8 with moderate priority and 8 and above with low priority.

Analysis of ranking by Cp values show that sub watersheds viz. Makraon has very high susceptibility to flash floods. The sub watersheds will have the quickest hydrological response in rainfall or storm events leading to lesser lag time. Four sub watersheds viz. Jamgad, Kali, Kaneri and Narora have shown high flash flood susceptibility and high downstream flood vulnerability, as compared to the sub watersheds showing moderate hazard such as Bainali, Bhikiyasen, Gagas sub, Khar, Malla and Riskan sub watersheds. Among the 13 sub watersheds Dusad and Khirao are least susceptible to the flash flood risks, which make this group as having a good potential for groundwater recharge as well (Figure 7).

Table 5: *Ranking of Flash Flood Susceptibility of Different Sub Watersheds of Gagas Basin*

	Sub Watersheds	Bainali	Bhikiyasen	Dusad	Gagas Sub	Jamga-d	Kali	Kaneri	Khar	Khir-ao	Makra-on	Malla	Narora	Riskan
Parameters	Sg	8	6	12	4	7	1	3	11	9	2	10	5	13
	WRbm	11	12	8	10	5	2	3	4	5	1	7	6	9
	Dt	7	13	9	3	6	12	10	4	11	8	5	1	2
	D	5	8	10	4	6	7	11	9	8	1	9	3	2
	Lg	5	8	11	4	6	7	12	9	8	1	10	3	2
	A	5	1	6	13	8	2	4	12	7	3	9	11	10

	Rf	10	3	12	6	2	9	7	8	13	4	5	1	11
	Re	4	10	2	7	11	5	6	6	1	9	8	12	3
	Rc	6	3	11	10	4	8	6	7	12	1	5	2	9
	Cc	6	3	11	10	4	8	5	7	12	1	4	2	9
	Rr	5	4	12	6	8	1	2	11	9	3	10	7	13
Slope Categories	**0°–0.3°**	4	11	10	11	2	8	5	7	12	6	1	9	3
	0.3°–1.1°	6	2	11	13	4	1	3	9	12	8	5	10	7
	1.1°–3.0°	6	1	11	13	3	4	2	8	12	7	5	10	9
	3.0°–5.0°	10	2	12	11	3	4	1	8	13	5	7	6	9
	5.0°–8.5°	7	2	12	8	3	4	1	6	13	11	9	5	10
	8.5°–16.5°	8	13	3	11	9	7	12	5	1	2	6	10	4
	16.5°–24°	11	8	7	13	5	6	3	2	12	1	10	9	4
	24°–35°	4	1	11	8	3	6	2	10	13	12	7	5	9
	35°–45°	5	2	13	1	6	4	7	9	12	11	8	3	10
	> 45°	6	12	13	1	10	2	8	4	9	5	11	3	7
WI		10	12	7	1	6	13	9	2	8	11	5	3	4
Q		9	13	8	1	6	12	10	2	7	11	5	3	4
Cp Value		6.87	6.52	9.65	7.35	5.52	5.78	5.74	6.96	9.52	5.39	7.00	5.61	7.09
RANKING		**Moder-ate**	**Moderate**	**Low**	**Moder-ate**	**High**	**High**	**High**	**Mode-rate**	**Low**	**Very High**	**Mode-rate**	**High**	**Modera-te**

Stream grade (Sg), Weighted mean bifurcation ratio (Rbm), Drainage texture (Dt), Drainage density (D), Length of overland flow (Lg), Basin area (A), Form factor (Rf), Elongation ratio (Re), Circulatory ratio (Rc), Compactness coefficient (Cc), Relative relief (Rr), Wetness Index (WI), Maximum discharge (Q)

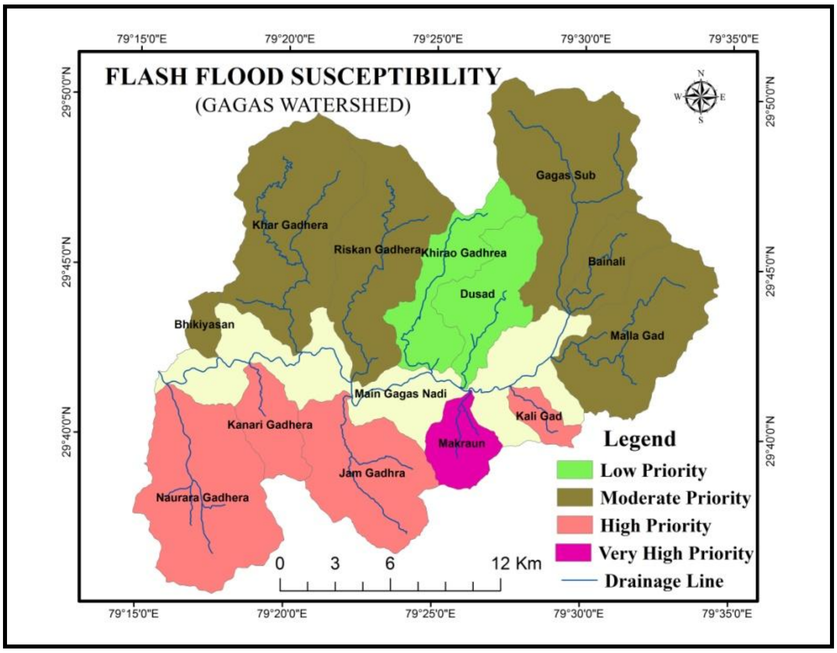

Figure 7: *Map of Flash Flood Susceptibility in Gagas Watershed*

6. Conclusion

In complex mountainous environment such as Himalayas, along with the topography having a major role in seasonal flooding, the effects of climate change render the region vulnerable to the natural hazards. As the primary determinants of running water systems functioning at the watershed scale, the physical (morphometrical, topographical) and climatic attributes were evaluated using remotely sensed data (ASTER-DEM) and GIS based approach.

The present study is carried out in the sixth order Gagas watershed in the Lesser Himalaya. In the study area, the drainage patterns are dendritic, that indicates impervious and non-porous bed rock. More number of higher order tributaries shows the association with more discharge and higher velocity of the stream flows. A detailed sub watershed study analysed 14 relevant parameters to assess flash flood susceptibility. The stream grade ranges from 3.74 % to 15.02 % showing the difference in the slope of the channel and thus the intensity of runoff at various reaches. The weighted mean bifurcation ratio ranges between 3.36 and 5.89, higher range show more elongated sub watersheds. Similar values express similar rock group composition and tectonic history, uniform climate conditions, infiltration rate and in similar stage of development. Drainage texture shows coarse (Bhikiyasen) texture showing massive and resistant rocks to very fine texture (Narora) expressing soft or weak rocks uncovered by vegetation. A relatively higher Drainage density (Makraun) shows a high density of streams, low infiltration and higher peak runoff. The sub watersheds sizes vary between 5.25 - 63.05 Km^2 affecting the lag time after heavy rainfall. In the analysis of relation between the order of tributaries; and shape factors (form factors, circulatory ratios, elongation ratios and compactness coefficient), it is observed that these are significant parameters in drainage-basin evolution as well as in influencing runoff.

The watershed has an average relative relief of 3.96%. The basin is characterised with level to very steep slope of the terrain ranging from lowest 0°–0.3° (01%) to >45° (0.51%). In the watershed maximum area falls in the slope category of 24°–35° (36.5%). Another important parameter of wetness index represents the spatial distribution of soil moisture, surface saturation and surface runoff. Its values range between 11378 (Gagas sub) showing potentially wetter region and more runoff generation and lowest 5112 (Kali) depicting a dry landscape. As a function of area, maximum discharge was calculated to estimate the potential hazard of flash floods. It varied between 49.87 m^3/s (Gagas sub) to 8.82 m^3/s (Bhikiyasen) and an average maximum discharge 30.69 m^3/s.

The RS/GIS techniques have been efficient tools in the understanding of drainage characteristics that help in the hazard risk mapping and having more accurate and reliable results as compared to conventional methods. In the study, one sub watershed (Makraon) have shown very high susceptibility to flash floods, while four sub watersheds viz. Jamgad, Kali, Kaneri and Narora have shown high susceptibility and high downstream flash flood vulnerability, as compared to those with moderate hazards such as Bainali, Bhikiyasen, Gagas sub, Khar, Malla and Riskan. Among the 13 sub watersheds, Dusad and Khirao are least susceptible to flash flood risks and having a good potential for groundwater recharge. As a management technique, various adaptive mechanisms to hazards such as water stress as well as peak runoff should be followed up. Building up of check dams, small ponds, storage water tanks, proper agriculture calendar could serve as measures for the prevention of losses occurred due to flash floods and mitigation of the water related disasters.

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