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PRIORITIZING WATERSHEDS FOR FLOOD RISK ASSESSMENT IN UTTARAKHAND HIMALAYAS USING GEOSPATIAL TECHNIQUES AND TOPSIS METHOD

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Abstract
Uttarakhand has a highly diverse topography, with snow-covered peaks, deep canyons, roaring streams, and dusty plains, all drained by various rivers of the Ganges system, India. The present study prioritizes watersheds in the Uttarakhand Himalayas for flood susceptibility using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, supported by GIS and remote sensing data. ALOS PALSAR Digital Elevation Model (DEM) with 12.5-meter resolution was utilized to map topographic features and to analyze 18 morphometric parameters of 28 watersheds. The TOPSIS method prioritized sub-watersheds using AHP criteria weights, which are classified into five priority levels ranging from very low to very high. The Sarju, Ram Ganga, and Song watersheds were identified as having the highest flood risk, placing them in the “Very High” priority class. These watersheds exhibited high drainage density (Dd), stream frequency (Fs), and bifurcation ratio (Rb), indicating a dense and complex drainage network prone to rapid runoff and increased flood potential. The watersheds such as Bandagarh, Parry, and Chandra Bhaga were placed in the “Very Low” priority class due to lower closeness coefficient (Cci) values, suggesting simpler drainage systems and reduced flood risk. The AUC (Area Under Curve) value of 0.789, indicates a good predictive accuracy for the TOPSIS model. The classification helps in pinpointing high-risk areas that require urgent flood management interventions.

Keywords: Morphometry, Watershed, Flood, Uttarakhand, AHP, TOPSIS, GIS

1. Introduction

River floods occur when the water level in a river or stream surpasses its capacity, causing the water to overflow onto the surrounding land and the flood risk is the probability of a flood happening and the potential impact it could have on people, property, and the environment (Merz et al., 2021). Floods are one of the most devastating types of extreme weather events. Between 1995 and 2015 all over the world, more than 2.2 billion people were impacted by floods, accounting for 53% of all individuals affected by weather-related disasters (United Nations, 2015). Floods also pose a significant vulnerability to India. Approximately 40 million hectares of the whole geographical area of 329 million hectares are susceptible to flooding. Annually, floods impact an average of 7.5 million hectares of land, resulting in the loss of 1600 lives and causing damage to crops, settlements, and public services amounting to 18050 million (National Disaster Management Authority Government of India, 2024).The Uttarakhand Himalaya, one of the integrated parts of the Himalaya, is the most fragile landscape and prone to geo-hydrological hazards such as floods (Sati & Kumar, 2022). In the recent past Uttarakhand experienced very heavy non-seasonal rainfall on 17, 18 and 19 Oct 2021, causing 79 persons dead, 24 injured and 03 missing and 1397 persons were evacuated by National Disaster Response Force (NDRF) (IAG Uttarakhand, 2021). Thus, prioritizing watersheds based on flood risk is crucial for effective flood management in this region.

Numerous studies have investigated flood hazards and vulnerabilities by utilizing diverse approaches (Baky et al., 2020; Ferk et al., 2020; Ghosh & Ghosal, 2021; Komolafe et al., 2021; Shah et al., 2018). But the recent studies evident that remote sensing and GIS techniques have been widely employed for flood inundation mapping (Aichi et al., 2024; Desalegn & Mulu, 2021; Diriba et al., 2024; Khoirunisa et al., 2021; Saikh & Mondal, 2023). Also, the multi-criteria decision-making methods have gained traction for flood susceptibility assessment (Dano et al., 2019; Ekmekcioğlu et al., 2021; Lee et al., 2015; Mitra & Das, 2023). Several national and international studies have highlighted the TOPSIS model as an effective and appropriate method for prioritizing areas of study (Abdolazimi et al., 2021; Ekmekcioğlu et al., 2021; Jozaghi et al., 2018; Luo et al., 2024; Meshram et al., 2020; Mitra & Das, 2023; Patel et al., 2022; Pathan et al., 2022; Shirani & Zakerinejad, 2021). However, research specifically focusing on prioritizing watersheds for flood risk reduction in the Uttarakhand Himalayas using a combination of geospatial techniques and the TOPSIS method remains limited. This study aims to develop a comprehensive framework for prioritizing watersheds in the Uttarakhand Himalayas based on their flood risk. The research involves a multi-stage approach, beginning with the delineation of watersheds using ALOS PASAR Digital Elevation Models. Following this, morphometric analysis will be conducted to quantify various watershed characteristics, that helps to understand hydrological and geomorphological processes by analyzing the geometric properties of a drainage basin or watershed, such as shape, size, relief, and spatial arrangement (R. E. Horton, 1945; S. Schumm, 1950; A. N.

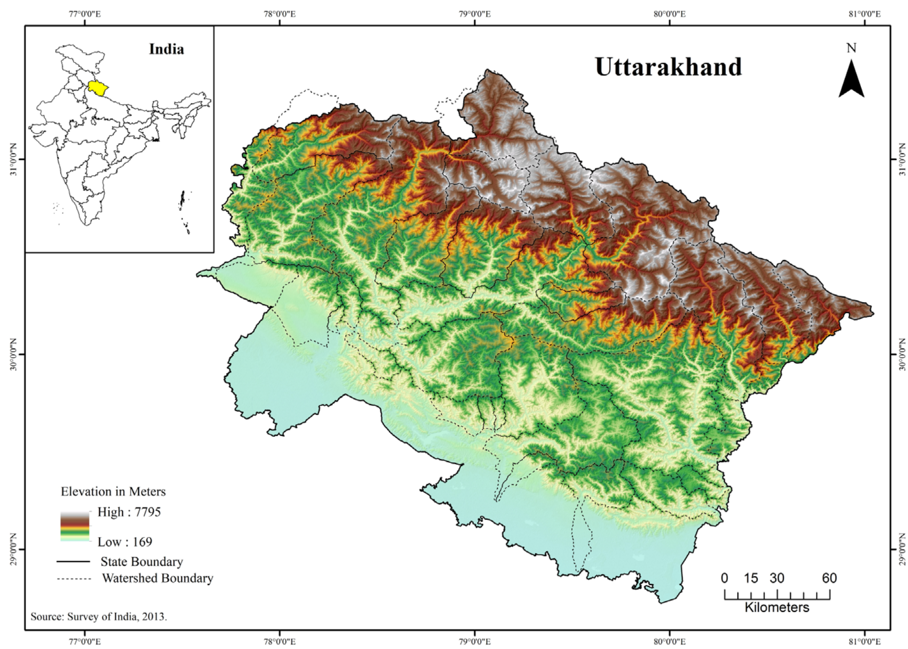

Fig. 1. Map of the study area

Strahler, 1952). The Analytical Hierarchy Process will be employed to assign weights to each parameter. Finally, the TOPSIS method will be applied to rank the watersheds based on their weighted flood risk indices, derived from the morphometric analysis and AHP weighting.

2. Study Area

Uttarakhand, located in the northern part of India, lies between 28.7347° N to 31.2914° N and 77.5788° E to 81.0109° E (Fig. 1). The state is characterized by its diverse topography, ranging from the low-lying plains of the Terai region in the south to the high Himalayan peaks in the north. The state experiences a range of climates due to its varying elevations. The lower regions have a subtropical climate, while the higher areas have an alpine climate with cold winters and mild summers. The monsoon season from June to September brings heavy rainfall, especially in the hilly areas, which can lead to landslides and floods. Geologically, Uttarakhand is a part of the Himalayan Mountain range, characterized by young folded mountains and deep valleys. Uttarakhand is known for its numerous rivers, which are crucial to the region's ecosystem and agriculture. The major rivers include the Ganges, Yamuna, Bhagirathi, Alaknanda, and Kali, which flow through the state, providing water for irrigation and hydropower generation.

3. Materials and Methods

Data Base

In this study, researchers employed a multifaceted approach, combining Remote Sensing (RS) techniques with Geographic Information System (GIS) methods to meticulously gather quantitative data on various basin features and thematic layers.

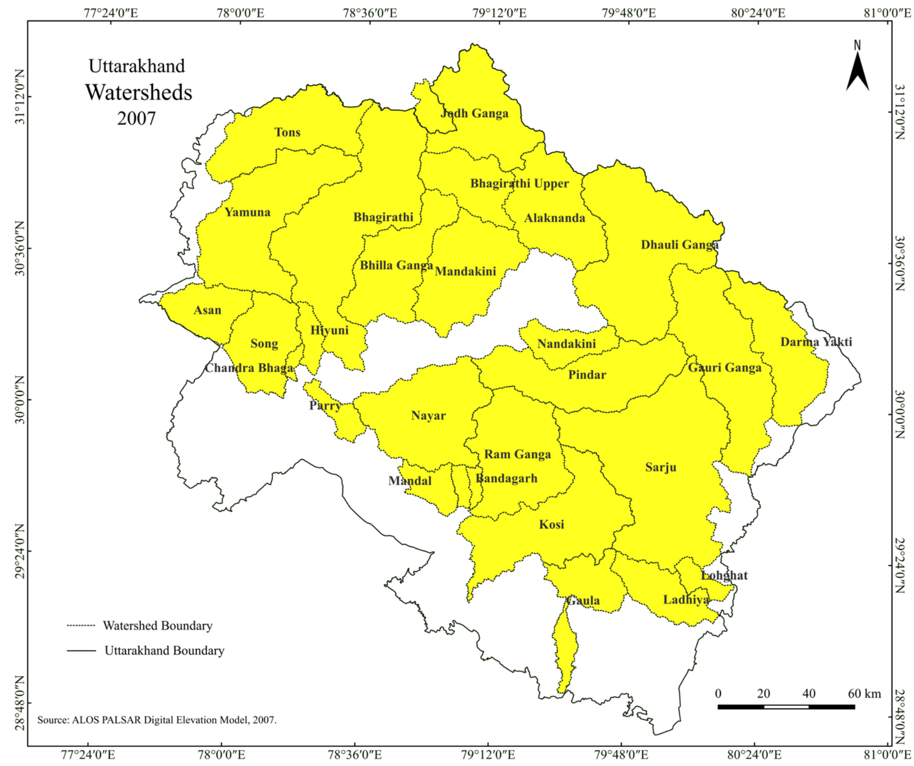

Fig. 2. Map of watersheds in the study area

Table 1. Morphometric parameters with their respective formulae

S. No.	Parameters	Symbol	Formula	Reference
			Linear Aspects	
1	Stream Order	Sμ	Finger tips streams are called "first order". Two first order streams join to form second order stream; two second order streams join to form a third order, and so on.	(A. N. Strahler, 1964)
2	Stream Number	Nu	Number of streams on any particular order.	(R. E. Horton, 1945)
3	Bifurcation Ratio	Rb	Rb = Nμ / Nμ + 1 Where, Nμ = No. of stream segments of a given order and Nμ + 1= No. of stream segments of next higher order.	(S. Schumm, 1956)
4	Mean Bifurcation Ratio	Rbm	Rbm = Average of bifurcation ratios of all orders	(A. N. Strahler, 1964)
			Areal Aspects	
5	Basin Area	A	Area from which water drains to a common stream and boundary determined by opposite ridges.	(A. N. Strahler, 1964)
6	Basin Perimeter	P	P = Outer boundary of drainage basin measured in kilometres.	(S. Schumm, 1956)
7	Basin Length	Lb	Length from origin of stream to its mouth.	(S. Schumm, 1956)
8	Stream Frequency	Fs	The ratio of the total number of streams (Nμ) of all orders in a catchment and the basin area.	(A. N. Strahler, 1964)
9	Drainage Density	Dd	Dd = Lμ /A Where, Lμ = Total stream length of all orders and A = Area of the basin (Km^2).	(S. Singh & Singh, 1997)
10	Drainage Texture	Dt	Dt = Nμ / P Where, Nμ = No. of streams in a given order and P = Perimeter (Kms).	(R. E. Horton, 1945)
11	Form Factor	Rf	Rf = A / Lb2 Where, A = Area of basin and Lb = Length of basin.	(R. E. Horton, 1945)
12	Elongation Ratio	Re	Re = √A /π / Lb Where, A = Area of the basin (Km2) Lb = Basin length (Km).	(S. Schumm, 1956)
13	Circularity Ratio	Rc	Rc = 4πA / P2 Where, A = Basin area (Km^2) and P = Perimeter of the basin (Km).	(Sharma et al., 2013)
			Relief Aspects	
14	Basin Relief	Bh	Bh = H - h Where, H = Maximum elevation of the basin (m) and h = Minimum elevation of the basin (m).	(Rudraiah et al., 2008)
15	Relief Ratio	Rr	Rr = H / Lb Where, H = basin relief (m) and Lb = Basin length (m)	(Rudraiah et al., 2008)
16	Ruggedness Number	Rn	Rn = Bh X Dd Where, Bh = basin relief and Dd = drainage density.	(S. Schumm, 1956)

Delving into the intricate topography of the basin, researchers accurately mapped out the relief and slope characteristics utilizing an ALOS PALSAR Digital Elevation Model (DEM) with an impressive resolution of 12.5 meters, sourced from the Alaska Satellite Facility (ASF) (https://asf.alaska.edu/). Drawing upon historical cartographic resources, the study utilized topographical maps of Uttarakhand meticulously crafted at a scale of 1:50,000 by the Survey of India (SoI) in 2007. Additionally, the study benefited from the utilization of geological maps provided by the Geological Survey of India.

Methodology

The ALOS PALSAR DEM (Digital Elevation Model) was instrumental in delineating the boundaries of the drainage basin and generating slope and contour maps. To ensure accuracy and compatibility, the ALOS PALSAR DEM was georeferenced using ArcGIS software and projected onto the UTM coordinate system, specifically WGS 1984 Zone 44/N. The initial steps involved in extracting the drainage network included gap filling within the DEM and subsequent calculation of slope, flow direction, flow accumulation, and stream order. These tasks were efficiently carried out using tools available in the spatial analyst and ArcHydro sections of the ArcToolbox. In this study, a comprehensive set of 16 morphometric parameters were considered to characterize the geometric features of the drainage basin (Table 1). The analytical framework for assessing drainage networks drew upon principles proposed by Horton in 1945, while the stream ordering approach developed by Strahler in 1964 was employed to determine the order of the streams (Kumar & Jayappa, 2011). With the use of the AHP and TOPSIS MCDM models, a total of 28 watersheds of Uttarakhand Himalayas (Fig. 2) ranked in terms of their importance for flood risk assessment.

AHP

The Analytic Hierarchy Process (AHP) is a multicriteria decision-making method that begins with identifying criteria relevant to the prioritization, such as morphometric parameters and flood susceptibility factors (Arulbalaji et al., 2019; Hembram & Saha, 2020). These criteria are then compared pairwise to establish their relative importance, using a scale from 1 to 9 based on Saaty's fundamental scale. The consistency of these judgments is evaluated through consistency ratios to ensure the reliability of the comparisons made. The criteria weights are calculated by synthesizing the pairwise comparison matrices using the eigenvector method. These weights are used to calculate the overall scores of the watersheds based on the criteria, allowing for their ranking to determine their priority levels for flood risk assessment and mitigation.

3.2.2. TOPSIS Method

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method prioritizes watersheds for flood susceptibility assessment by assigning weights to various morphometric parameters based on their significance in flood occurrence (Alvandi et al., 2021; Mohammadi et al., 2022). This method ranks watersheds according to their proximity to the ideal solution and farthest distance from the negative ideal solution, categorizing them into different classes based on their performance scores. The following are the steps to rank watersheds using the TOPSIS Method.

1. Calculating the normalized decision matrix.

$$R_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}}$$

where, R_{ij} is a normalized decision matrix element and a_{ij} is the i^{th} alternative performance in jth criteria.

2. Calculation of the weighted normalized decision matrix.

$$V_{ij} = R_{ij} X w_j$$

where, Vij is weighted normalized matrix element, Rij is normalized matrix elements, and Wj is weight of criteria j.

3. Determining the positive ideal solution (PIS) and negative ideal solution (NIS)

$$A^+ = \{(maxV_{ij}|j \in J), (minV_{ij}|j \in J)i = 1,2, \ldots..m\}$$
$$= \{V_1^+, V_2^+, V_3^+, \ldots. V_j^+ \ldots\ldots V_n^+\}$$
$$A^- = \{(maxV_{ij}|j \in J), (minV_{ij}|j \in J)i = 1,2, \ldots..m\}$$
$$= \{V_1^-, V_2^-, V_3^-, \ldots. V_j^- \ldots\ldots V_n^-\}$$

where, j and J are related to increasing and decreasing criteria, respectively.

4. Measuring the ideal and negative ideal solution distanceű

$$d_{i+} = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j^+)^2}; i = 1,2, \ldots..m$$
$$d_{i-} = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j^-)^2}; i = 1,2, \ldots..m$$

5. The final step is to compute the closeness coefficient. This coefficient indicates how close each alternative is to the ideal solution.

$$cl_{i+} = \frac{d_{i-}}{d_{i+} + d_{i-}}; 0<cl_{i+}<1; i= 1,2, \ldots m.$$

where, cli+ is closeness coefficient, di+ is positive ideal solution (PIS), and di− is negative ideal solution (NIS).

3.2.3 AUROC

The Area Under the Receiver Operating Characteristic Curve (AUROC) is a widely used statistical method to validate the predictive performance of a classification model, especially when the model outputs probabilities or continuous scores. AUROC quantifies the model's ability to discriminate between two classes, in this case, flood occurrence (positive) and no flood occurrence (negative). A higher AUROC value indicates better model performance, where 1.0 represents perfect discrimination, 0.5 indicates random prediction, and values between 0.7 to 0.9 signify reasonable to excellent accuracy. The primary advantage of using AUROC is that it evaluates the model across all possible thresholds, providing a robust measure unaffected by imbalanced class distributions. The procedure for calculating AUROC involves the following steps:

1. Compute the True Positive Rate (TPR) and False Positive Rate (FPR) at various decision thresholds.

$$TPR = \frac{TP}{TP+FN}$$

$$FPR = \frac{FP}{FP+TN}$$

Where, True Negatives is TN, False Positives is FP, False Negatives is FN, True Positives is TP.

2. Plot TPR (y-axis) against FPR (x-axis) for all possible thresholds ranging from 0 to 1.

3. The AUROC value is computed using numerical integration technique.

$$AUC = \sum_{i=1}^{n} \frac{(FPR_i - FPR_{i-1}) X (TPR_i + TPR_{i+1})}{2}$$

4. Results

Morphometric Parameters

The study area is delineated into 28 distinct watersheds of varying sizes (Fig. 2). For each of these watersheds, 16 morphometric parameters encompassing linear, areal, and relief aspects were analyzed to assess and prioritize their flood susceptibility (Table 1). The comprehensive results of this analysis are presented in Table 2.

Linear Morphometric Parameters

The linear morphometric parameters, including stream number, bifurcation ratio, and stream order, were thoroughly analyzed and are presented in Table 2. Notably, some watersheds exhibit a maximum stream order of 7, highlighting their complex drainage network and potential implications for hydrological behavior (Fig. 3).

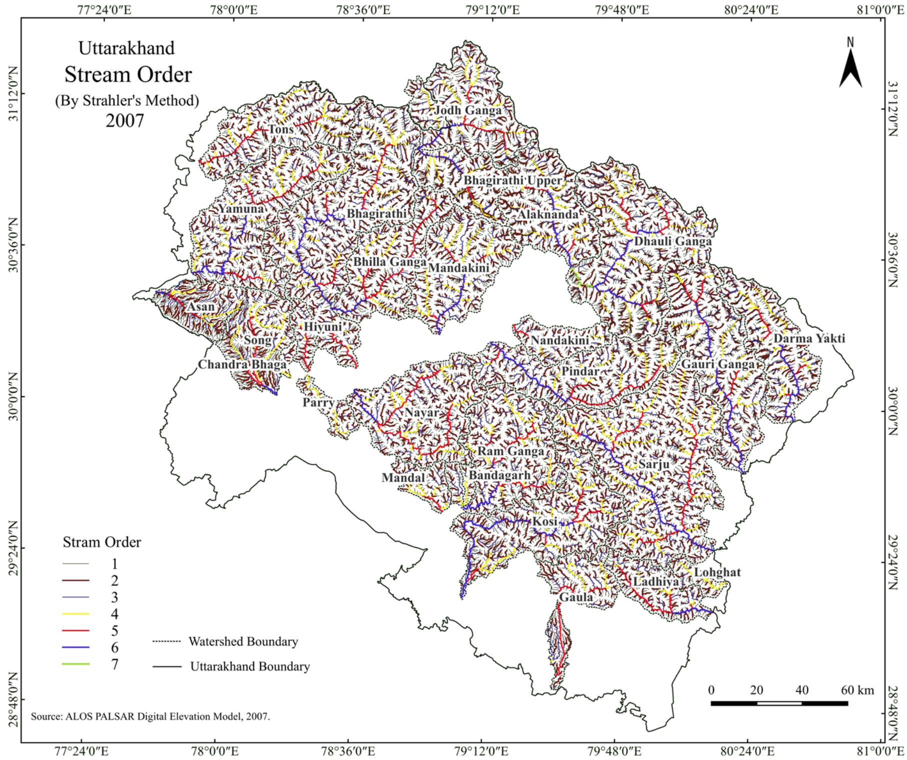

Fig. 3. Stream order of all the watersheds in study area

Stream Number

The stream number is calculated based on the number of stream segments of each order, forming an inverse geometric sequence with an order number (R. E. Horton, 1932). Stream number is directly correlated with discharge and is used to determine the peak discharge of streams. Watersheds like Sarju (3263) and Bhagirathi (2782) exhibit a relatively high number of streams across different orders, suggesting a dense and well-developed drainage network. On the other hand, watersheds like Chandra Bhaga (56) and Lohghat (189) display lower stream numbers, indicative of less intricate drainage systems.

Bifurcation Ratio (Rb)

Bifurcation ratio is a dimensionless parameter that expresses the ratio of the number of streams of any given order to the number in the next lower order (M. & Aditya, 2014; Syed & Nazia, 2013). Rbm (mean bifurcation ratio) for various watersheds, ranging from 2.33 to 6.15. A higher Rbm can lead to faster runoff and increased flood risk, especially during heavy rainfall. The Gaula river has the highest Rbm value of 6.15, indicating a highly branched stream network. Conversely, lower Rbm values indicate a less interconnected stream network, potentially resulting in slower runoff and reduced flood risk.

Areal Morphometric Parameters

Watershed area (A) is the total area enclosed in the watershed boundary. It is directly used to find the other areal aspects such as drainage density (Dd) and stream frequency (Fs). Other aspects such as form factor (Ff), circulatory ratio (Rc) and elongation ratio (Re) are used to describe the impact of shape of basin on flood susceptibility. All these listed in table 2.

Table 2. Linear, Areal and Relief Morphometric Parameters

Watersheds	Linear		Areal										Relief				
	Σ Nu	Rbm	A in sq. km	P in km	BL in km	Ff	Re	Rc	Bs	Dd	Fs	Dt	Max 'H'	Min 'h'	Bh	Rr	Rn
Alaknanda	1363.00	4.05	1534.03	210.32	58.88	0.44	0.75	0.44	2.26	1.14	0.89	6.48	7707	1456	6.25	0.11	7.10
Asan	525.00	3.69	699.87	139.26	39.42	0.45	0.76	0.45	2.22	1.42	0.75	3.77	2356	389	1.97	0.05	2.79
Bandagarh	71.00	3.92	91.80	56.14	19.45	0.24	0.56	0.37	4.12	0.92	0.77	1.26	2402	540	1.86	0.10	1.71
Bhagirathi	2782.00	4.69	3449.76	410.70	115.66	0.26	0.57	0.26	3.88	0.99	0.81	6.77	6645	469	6.18	0.05	6.13
Bhagirathi Upper	827.00	3.79	902.19	160.11	51.07	0.35	0.66	0.44	2.89	1.17	0.92	5.17	7097	2696	4.40	0.09	5.17
Bhilla Ganga	1171.00	4.16	1482.43	237.37	72.44	0.28	0.60	0.33	3.54	0.98	0.79	4.93	6615	776	5.84	0.08	5.71
Chandra Bhaga	56.00	2.33	76.47	53.15	16.40	0.28	0.60	0.34	3.52	1.09	0.73	1.05	2112	337	1.78	0.11	1.94
Darma Yakti	1261.00	4.08	1365.68	231.96	75.12	0.24	0.55	0.32	4.13	1.07	0.92	5.44	6823	1118	5.71	0.08	6.11
Devta Gadhera	84.00	4.58	121.84	56.22	19.19	0.33	0.65	0.48	3.02	0.97	0.69	1.49	2403	545	1.86	0.10	1.78
Dhauli Ganga	2607.00	4.12	3031.69	323.78	66.76	0.68	0.93	0.36	1.47	1.09	0.86	8.05	7795	1438	6.36	0.10	6.90
Gaula	1098.00	6.15	848.18	291.02	66.54	0.19	0.49	0.13	5.22	1.07	1.29	3.77	2595	186	2.41	0.04	2.57
Gauri Ganga	1963.00	4.42	2242.41	305.12	98.11	0.23	0.54	0.30	4.29	1.06	0.88	6.43	7411	606	6.81	0.07	7.18
Hiyuni	215.00	3.61	254.09	90.11	32.11	0.25	0.56	0.39	4.06	0.97	0.85	2.39	2661	369	2.29	0.07	2.23
Jodh Ganga	1371.00	4.27	1809.86	246.33	52.86	0.65	0.91	0.37	1.54	1.00	0.76	5.57	6890	2722	4.17	0.08	4.16
Kosi	1719.00	4.28	2158.84	366.14	85.49	0.30	0.61	0.20	3.39	1.06	0.80	4.69	2733	223	2.51	0.03	2.66
Ladhiya	616.00	3.53	739.94	167.60	53.47	0.26	0.57	0.33	3.86	1.04	0.83	3.68	2300	336	1.96	0.04	2.04
Lohghat	189.00	5.74	221.30	87.70	26.99	0.30	0.62	0.36	3.29	1.05	0.85	2.16	2208	380	1.83	0.07	1.93
Mandakini	1312.00	4.23	1642.69	211.39	56.66	0.51	0.81	0.46	1.95	0.98	0.80	6.21	6954	629	6.33	0.11	6.22
Mandal	276.00	4.01	362.99	109.47	31.04	0.38	0.69	0.38	2.65	0.99	0.76	2.52	2508	447	2.06	0.07	2.04
Nandakini	430.00	4.33	541.91	130.21	43.85	0.28	0.60	0.40	3.55	0.96	0.79	3.30	6794	838	5.96	0.14	5.71
Nayar	1520.00	4.55	1933.49	240.25	60.39	0.53	0.82	0.42	1.89	0.98	0.79	6.33	3081	426	2.66	0.04	2.59
Parry	227.00	5.82	283.21	103.73	32.18	0.27	0.59	0.33	3.66	0.98	0.80	2.19	1955	366	1.59	0.05	1.56
Pindar	1563.00	4.26	1897.17	274.38	84.10	0.27	0.58	0.32	3.73	0.99	0.82	5.70	6839	734	6.11	0.07	5.98
Ram Ganga	1461.00	4.28	1851.09	237.74	56.24	0.59	0.86	0.41	1.71	2.15	0.79	6.15	3077	529	2.55	0.05	5.45
Sarju	3263.00	4.84	4047.96	418.06	87.78	0.53	0.82	0.29	1.90	0.98	0.81	7.81	6027	414	5.61	0.06	5.50
Song	2130.00	6.11	1050.89	174.26	48.71	0.44	0.75	0.43	2.26	1.29	2.03	12.22	2751	304	2.45	0.05	3.13
Tons	1312.00	5.92	1614.84	244.79	78.69	0.26	0.58	0.34	3.83	0.98	0.81	5.36	6313	645	5.67	0.07	5.55
Yamuna	1849.00	4.41	2339.21	310.99	87.25	0.31	0.63	0.30	3.25	0.97	0.79	5.95	6281	466	5.82	0.07	5.64

*Stream Number (Nu), Mean bifurcation ratio (Rbm), Area (A), Perimeter (P), Basin Length (BL), Form factor (Ff), Elongation ratio (Re), Circularity ratio (Rc), Shape factor (Bs), Drainage density (Dd), Drainage Texture (Dt), Stream frequency (Fs), Basin relief (Bh), Ruggedness number (Rn), and Relief rati

Drainage Density

It is a measure of the average length of streams per unit drainage area, and describes the spacing of drainage channels (Praveen et al., 2017). High Dd values indicate a well-developed drainage network, where water is rapidly channeled through streams and rivers, resulting in quick and concentrated surface runoff during rainfall events. The Ram Ganga watershed exhibits a high drainage density (2.15), along with Song (1.29), Gaula (1.07), and Dhauli Ganga (1.09), making them more susceptible to flooding due to their efficient drainage systems. In contrast, watersheds with lower Dd values, such as Sarju (0.98), Mandal (0.99), Pindar (0.99), and Bandagarh (0.92), tend to have less efficient drainage networks for floods.

Stream Frequency

It defines the total number of stream segments of all orders per unit area (R. E. Horton, 1932). Watersheds with high stream frequency, such as Song (2.03), Gaula (1.29), Dhauli Ganga (0.86), and Sarju (0.81), are more prone to rapid surface runoff due to their extensive stream networks, which can quickly convey water to the main channels and elevate flood risks. Conversely, watersheds with lower Fs values, such as Mandal (0.76), Bhagirathi Upper (0.92), Asan (0.75), and Devta Gadhera (0.69), have sparser drainage networks, which can lead to slower runoff and reduced flood potential.

Form Factor

Horton (1945) has described the form factor as determined by the ratio of the basin area to the square of the basin length. Its values range between 0 and 1. A higher Ff value indicates a more circular watershed, which tends to have a shorter runoff distance and higher peak flow during rainfall events, thereby increasing the potential for flash flooding. Watersheds with high Form Factor values, such as Asan (0.45), Alaknanda (0.44), Mandakini (0.51), and Sarju (0.53), are at high flood risk. In contrast, watersheds with lower Ff values, such as Gaula (0.19), Gauri Ganga (0.23), Nandakini (0.28), and Chandra Bhaga (0.28), have lower peak flows, which can reduce the immediate risk of flooding.

Circulatory Ratio (Rc)

The circulatory ratio (Rc) is defined as the ratio between the area of the basin and the area of a circle with the same perimeter as the basin (A. N. Strahler, 1964). Devta Gadhera (0.48), Mandakini (0.46), Alaknanda (0.44), and Asan (0.45) are among the watersheds with higher circulatory ratios. These higher values suggest that these watersheds are more circular and likely to experience quicker runoff, leading to higher peak flows and an increased risk of flash floods during rainfall events.

Elongation Ratio (Re)

The elongation ratio (Re) is defined as the ratio of the diameter of a circle with the same area as the basin (A) to the length of the basin (Lb) (S. Schumm, 1956b). A higher elongation ratio (Re close to 1.0) implies that the watershed is more circular, which is associated with quicker drainage and a higher potential for flash floods. Jodh Ganga (0.91), Ram Ganga (0.86), Ladhiya (0.57), and Bhilla Ganga (0.60) are among the watersheds with higher Re values. These watersheds, being more circular, are more likely to experience rapid runoff and higher peak flows, increasing the risk of flash floods during intense rainfall. Conversely, watersheds with lower elongation ratios, such as Gaula (0.49), Hiyuni (0.56), Bandagarh (0.56), and Bhagirathi (0.57), exhibit a more elongated shape. These watersheds may have a lower risk of sudden floods due to the elongated shape.

Drainage Texture (Dt)

"Drainage Texture refers to the total number of stream segments of all orders along the basin's perimeter" (R. E. Horton, 1932). Drainage texture is calculated by multiplying Dd and Fs (Sreedevi et al., 2009). Smith, 1950 distinguished five types of drainage texture (Dt): very coarse (less than 2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8), and very fine (> 8). The Song watershed has a high drainage texture of 12.22, indicating a very fine drainage texture, which suggests a high potential for quick runoff and flash floods. Watersheds such as Asan (3.77), Kosi (4.69), Lohghat (2.16), and Nandakini (3.30) show coarse to moderate drainage textures which indicate the low flood risk in these areas.

Relief Morphometric Parameters

Basin Relief

Basin relief (Bh) is the elevation difference between a watershed's highest and lowest points (S. Schumm, 1956). The basin relief (Bh) parameter strongly influences streams gradient, affecting flooding patterns and the amount of sediment transported (Farhan, 2017). The Alaknanda watershed has a high basin relief of 6.25 km, indicating significant elevation changes and steep terrain suggesting this regions are prone to rapid water flow and intense erosion processes. Conversely, watersheds such as Asan (1.97 km), Lohghat (1.83 km), Parry (1.59 km), and Chandra Bhaga (1.78 km) have lower basin relief, indicating gentler slopes and less pronounced elevation changes, leading to slower water flow and reduced erosion.

Relief Ratio (Rr)

The relief ratio (Rr) is defined as a dimensionless height-length ratio between the relief of the basin (Bh) and the length of the basin (Lb) (S. Schumm, 1956). High values are associated with hilly regions, and rapid discharges (Sreedevi et al., 2009). Watersheds with high relief ratios, such as Alaknanda (0.11), Mandakini (0.11), Chandra Bhaga (0.11), and Gauri Ganga (0.07), are characterized by steep slopes, leading to rapid water flow. These watersheds are more likely to experience flash floods.

Ruggedness Number (Rn)

The ruggedness number (Rn) is a dimensionless parameter that is calculated by multiplying the basin relief (Bh) by the drainage density (A. N. Strahler, 1964). Rn values are typically higher in mountainous regions having a tropical climate and abundant rainfall with active geomorphic processes (Farhan, 2017). The Dhauli Ganga watershed has a high ruggedness number of 6.90, signifying a highly rugged and dissected terrain with significant flood potential. Conversely, watersheds like Chandra Bhaga (1.94), Parry (1.56), Devta Gadhera (1.78), and Lohghat (1.93) have lower ruggedness numbers, suggesting smoother terrain with less pronounced surface irregularities and lower erosion potential.

Table 3. Pairwise comparison matrix

	Dd	Fs	Nu	Rc	Ff	Re	Rb	Rn	Dt
Dd	1	2	3	4	4	5	6	7	9
Fs	0.50	1	2	3	4	4	5	6	8
Nu	0.33	0.5	1	3	4	5	6	7	8
Rc	0.25	0.33	0.33	1	3	3	5	6	9
Ff	0.25	0.25	0.25	0.33	1	2	5	7	9
Re	0.20	0.25	0.2	0.33	0.5	1	5	7	8
Rb	0.17	0.2	0.17	0.2	0.2	0.2	1	2	4
Rn	0.14	0.17	0.14	0.17	0.14	0.14	0.5	1	3
Dt	0.11	0.13	0.13	0.11	0.11	0.13	0.25	0.33	1

Table 4. Normalized pair wise comparison matrix

	Dd	Fs	Nu	Rc	Ff	Re	Rb	Rn	Dt	Weightage
Dd	0.34	0.41	0.42	0.33	0.24	0.24	0.18	0.16	0.15	0.27
Fs	0.17	0.21	0.28	0.25	0.24	0.20	0.15	0.14	0.14	0.19
Nu	0.11	0.10	0.14	0.25	0.24	0.24	0.18	0.16	0.14	0.17
Rc	0.08	0.07	0.05	0.08	0.18	0.15	0.15	0.14	0.15	0.12
Ff	0.08	0.05	0.03	0.03	0.06	0.10	0.15	0.16	0.15	0.09
Re	0.07	0.05	0.03	0.03	0.03	0.05	0.15	0.16	0.14	0.08
Rb	0.06	0.04	0.02	0.02	0.01	0.01	0.03	0.05	0.07	0.03
Rn	0.05	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.05	0.02
Dt	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01

Table 5. Ranking of sub-watersheds based on TOPSIS

Watersheds	Di_{+ve}	Di_{-ve}	Cci	Ranks	Priority
Song	0.05	0.08	1.646	1	Very High
Ram_Ganga	0.06	0.07	1.168	2	Very High
Sarju	0.07	0.07	1.069	3	Very High
Dhauli Ganga	0.07	0.06	0.982	4	High
Bhagirathi	0.08	0.06	0.855	5	High
Gauri Ganga	0.08	0.04	0.621	6	High
Yamuna	0.08	0.04	0.551	7	Medium
Alaknanda Upper	0.08	0.04	0.542	8	Medium
Nayar	0.08	0.04	0.535	9	Medium
Jodh Ganga	0.08	0.04	0.514	10	Medium
Kosi	0.08	0.04	0.504	11	Medium
Mandakini	0.08	0.04	0.496	12	Low
Pindar	0.08	0.04	0.468	13	Low
Gaula	0.08	0.03	0.454	14	Low
Asan	0.09	0.04	0.441	15	Low
Darma Yakti	0.08	0.03	0.415	16	Low
Bhagirathi Upper	0.08	0.03	0.401	17	Low
Tons	0.09	0.03	0.398	18	Very Low
Bhilla Ganga	0.09	0.03	0.352	19	Very Low
Devta Gadhera	0.10	0.02	0.250	20	Very Low
Ladhiya	0.09	0.02	0.231	21	Very Low
Nandakini	0.10	0.02	0.229	22	Very Low
Mandal	0.10	0.02	0.216	23	Very Low
Lohghat	0.10	0.02	0.211	24	Very Low
Hiyuni	0.10	0.02	0.203	25	Very Low
Chandra Bhaga	0.10	0.02	0.176	26	Very Low
Parry	0.10	0.02	0.169	27	Very Low
Bandagarh	0.11	0.02	0.164	28	Very Low

4.2. Prioritization of the drainage basin

Multicriteria decision-making (MCDM) involves using various methods to evaluate and rank alternatives based on multiple criteria. The first step involves developing a hierarchy of criteria and alternatives. The Analytic Hierarchy Process (AHP) is then used to determine the relative importance of each criterion. Using the AHP (Table 3 & 4), the weights of each criterion, such as 'Dd,' 'Fs,' 'Nu,' 'Rc,' 'Ff,' 'Re,' 'Rb,' 'Rn,' and 'Dt,' were derived. These weights represent the importance of each criterion in the decision-making process (Table 4). Following the AHP process, the TOPSIS method is applied. A decision matrix is created with the performance values of each alternative for each criterion. Cci represents the closeness coefficient of each watershed, which is calculated as the ratio of the distance from the negative ideal solution to the sum of the distances from the negative and positive ideal solutions. A higher value of Cci indicates

Table 6: List of the flood occurrence in the Uttarakhand

Year	Flood Name/Location	River(s) Affected	Impact	Reference
1970	Alaknanda Flood	Alaknanda	Widespread destruction.	(Rana et al., 2013)
1991	Uttarkashi Flood	Bhagirathi	Major damage in Uttarkashi.	(Parkash, 2012)
1998	Malpa Landslide and Flood	Kali	250+ deaths, village destroyed.	(Paul et al., 2000)
2001	Phata Flood	Mandakini	27 people, 64 animals, 22 houses	(Naithani et al., 2002)
2009	Rudraprayag Flood	Mandakini	Minor flooding in Rudraprayag.	(Gairola & Bisht, 2012)
2012	Ukhimath	Mandakini	66 people	(Dimri et al., 2017)
2012	Pandrasu ridge	Ganga	35 people, 436 livestock lost, 591 houses damged	(Gupta et al., 2013)
2012	Uttarkashi Flood	Bhagirathi	Major damage in Uttarkashi.	(Gupta et al., 2013)
2012	Uttarakhand Flood	Alaknanda	Localized destruction.	(Parkash, 2012)
2013	Kedarnath Flood	Mandakini, Bhagirathi, Alaknanda	5,700+ deaths, massive destruction.	(Ahluwalia et al., 2016)
2014	Purala Flood	Tons	16 people reported dead	(Mishra et al., 2022)
2016	Kemra Flood	Bhagirathi	120 houses, 100 animals	(Gourav et al., 2020)
2016	Pithoragarh Flood	Sarju	Localized flooding, destruction.	(Parihar & Pandey, 2022)
2017	Dharchula Flood	Sarju	16 people	(Mani et al., n.d.)
2018	Tharali Flood	Pindar	55 houses, 10 vehicles, 2 ropeways	(Joshi et al., 2018)
2019	Makudi Flood	Bhagirathi	17 people died	(Chauhan et al., 2022)
2021	Chamoli Disaster	Rishiganga, Dhauliganga	200+ deaths, severe damage.	(Kansal & Singh, 2022)
2022	Seasonal Flooding	Song	Flash floods across the state.	(Khanduri, 2024)

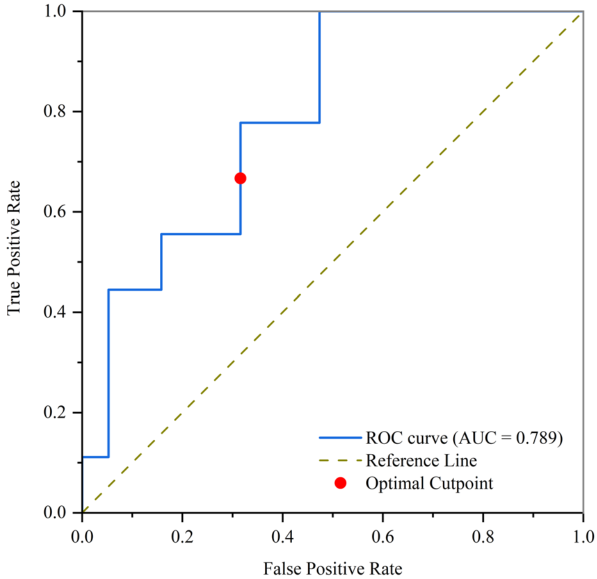

Fig. 4. Receiver Operating Characteristic (ROC) Curve and calculation of Area Under Curve (AUC)

that the watershed is closer to the negative ideal solution and therefore performs worse overall. The watersheds have been classified into five classes based on their Cci values (Table 4 & Fig. 5).

5. Validation of results through AUROC

To validate the flood occurrence predictions in various watersheds, Receiver Operating Characteristic (ROC) curve analysis is applied, and the Area Under the Curve (AUC) value is calculated. ROC analysis provides a graphical representation of the trade-off between the True Positive Rate (TPR) and the False Positive Rate (FPR) at various thresholds (Fig. 4). The data comprised 28 watersheds (Table 5 & 6), where flood occurrence (positive state) and no flood occurrence (negative state) were classified based on predictive values. The AUC for the TOPSIS model is calculated as 0.789 (Standard Error is 0.09837), with a 95% Confidence Interval. An AUC value of 0.789 indicates that the model has good discriminatory power, as it effectively differentiates between watersheds experiencing flood events and those without flood occurrence.

6. Discussion

The analysis revealed critical insights into the spatial variability of flood susceptibility across different watersheds in study area. Using morphometric parameters such as drainage density, bifurcation ratio, slope, elongation ratio, and relief ratios, the watersheds were prioritized based on their susceptibility to flooding. The Receiver Operating Characteristic (ROC) analysis further validated the results, yielding an Area Under the Curve (AUC) value of 0.789 with a standard error of 0.098, demonstrating acceptable performance and predictive accuracy. Watersheds such as the Alaknanda Upper, Bhagirathi, Dhauli Ganga, Mandakini, Sarju, and Song emerged as highly susceptible based on both morphometric analysis and flood occurrence data. The results underscore the crucial role of morphometric analysis in identifying flood-prone watersheds, particularly in regions like Uttarakhand, which are highly susceptible to natural disasters due to steep slopes, high relief, and intense precipitation. Watersheds exhibiting higher drainage density and relief values reflect faster runoff and higher potential for flooding. For example, watersheds such as Dhauli Ganga and Sarju show significant flood susceptibility due to their steep slopes and poor infiltration capacity. This aligns with findings from earlier studies done by Joshi et al., 2018 and Karmokar & De, 2020 where areas with high drainage density were observed to be highly correlated with flood events. The AUC value of 0.789, achieved through ROC curve analysis, indicates a good predictive accuracy for the model, validating the reliability of morphometric parameters in flood susceptibility analysis. The standard error of 0.098 further corroborates the precision of the assessment, as the deviation from the mean prediction remains minimal. Although not perfect, the acceptable predictive ability suggests that the morphometric parameters used are meaningful indicators for flood potential analysis.

The findings of this study hold significant practical relevance for regional flood management and policy formulation. By identifying flood-prone watersheds using validated morphometric parameters, stakeholders such as policymakers, watershed managers, and disaster risk authorities can allocate resources more effectively for flood mitigation and preparedness. For instance, highly susceptible watersheds like Sarju and Dhauli Ganga should be prioritized for the implementation of flood-resistant infrastructure, afforestation programs, and sustainable land use practices. While the results provide a comprehensive assessment of flood susceptibility, a few limitations are persist. First, the reliance on morphometric parameters alone may not fully capture the dynamic nature of flood occurrence. Parameters such as land use changes, soil infiltration capacity, and real-time hydrological data were not incorporated due to data constraints, which could impact the overall accuracy of the results. Second, the AUROC value of 0.789, although indicative of good accuracy, highlights a certain margin of error in the model predictions. Also,

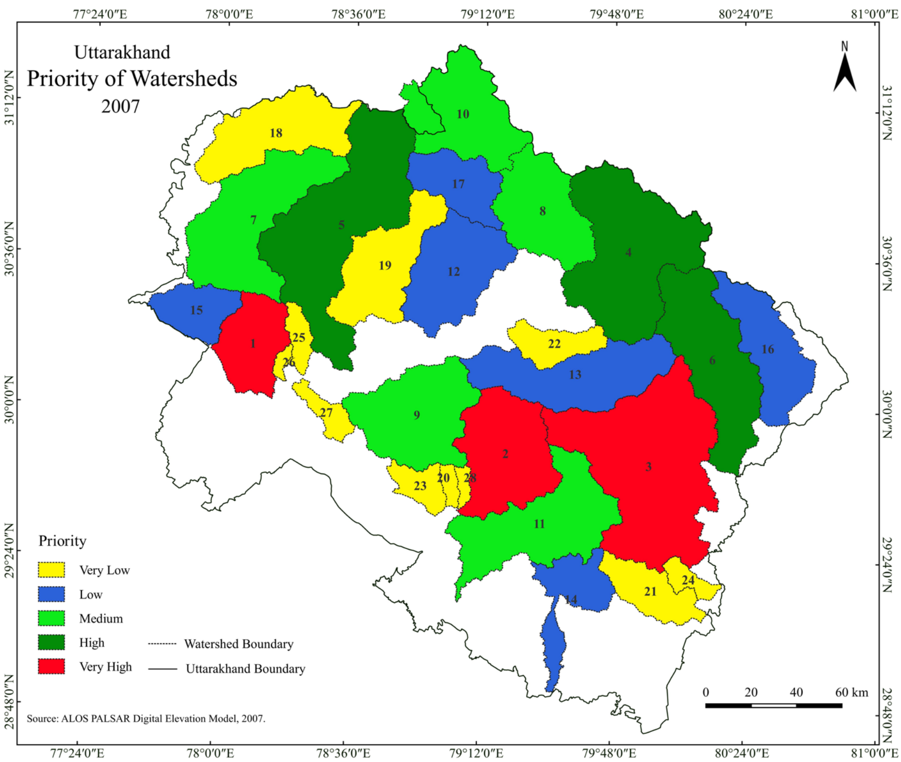

Fig. 5. Priority ranks of the watersheds for flood susceptibility

the validation process primarily relied on historical flood occurrence data, which may not account for unforeseen climatic variations or extreme events occurring in the future. So, the future studies should integrate a broader range of parameters, such as climatic variables (e.g., precipitation patterns, temperature), anthropogenic influences, and remote sensing-derived land use/land cover changes, to improve the accuracy and reliability of flood susceptibility models. There is a need for long-term flood monitoring and community-based flood management programs in highly susceptible watersheds. The collaboration between researchers, policymakers, and local communities can foster resilience against flood hazards by implementing effective water resource management, land-use policies, and infrastructural interventions.

7. Conclusion

The results of the study demonstrate the critical role of morphometric parameters in flood susceptibility assessment, particularly in regions with challenging geomorphic and hydrological characteristics. The application of ROC curve analysis validated the reliability of the results, with an AUC value of 0.789 indicating acceptable predictive performance. Watersheds like Sarju and Bhagirathi, with high stream numbers and bifurcation ratios, are identified as having elevated flood risks due to their propensity for reduced infiltration and increased runoff. Conversely, watersheds such as Chandra Bhaga and Bandagarh, which exhibit lower stream frequencies and bifurcation ratios, are associated with reduced flood risks. Overall, this study provides valuable insights for decision-makers, offering a scientific basis for prioritizing watersheds and implementing effective flood mitigation strategies in the region. The findings emphasize the importance of integrating morphometric analysis with advanced decision-making techniques to address the growing challenges of flood management in the Uttarakhand Himalayas.

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