Mapping and Prioritizing Flash-Flood Susceptible Watersheds in the Warana Basin, India: A Morphometric Analysis and Total Ranking Approach for Resilience Planning

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Abstract: The efficiency of flood management is greatly influenced by the physical characteristics of a river basin. Morphometric Analysis is a prominent method used for quantitatively analyzing a river basin. In this study, 22 parameters were selected, some directly and some inversely related to flash floods, from various aspects such as basic, linear, shape, relief, and hypsometric, for the Warana River basin. We delineated 13 sub-watersheds and employed GIS techniques to directly measure basic parameters from the DEM, while others were calculated using mathematical formulas. The sub-watersheds of the Warana basin were prioritized using the total rank method. The morphometric analysis revealed that the Warana basin was a sixth-order basin with a total area of nearly 2085 km^2, a length of 104.75 km, and a perimeter of 460 km. The mean bifurcation ratio of 1.79 indicates a structurally less-disturbed watershed. However, despite the low structural disturbance, 8 out of the 13 sub-watersheds, accounting for 59.5% of the area, were highly susceptible to flooding, ranging from high to very high susceptibility. The outputss of this study can be utilized by relevant authorities to implement appropriate measures for reducing losses caused by flash floods and the development of prevention, protection, and mitigation plans.

Keywords: Warana, ArcSWAT, Morphometric analysis, Flash flood, Prioritization, Geospatial Technology

1. Introduction

India is a region highly susceptible to natural disasters, leading to significant property damage, infrastructure loss, and loss of human life each year. Among these disasters, floods pose a major threat globally and account for more than one-third of the total losses in Asia, amounting to 517 billion USD over the past 50 years (Sharma, 2021). The effectiveness of flood management is contingent upon a multitude of factors, encompassing flood magnitude, intensity, recurrence interval, flow duration, and alterations in the morphology of both the river and its floodplain. Remote sensing and hydrological models have emerged as valuable tools for rapidly and comprehensively studying flood hazards and disasters worldwide. By utilizing remote sensing datasets before and after floods, flood mapping can be conducted to predict future flood situations and plan for effective mitigation strategies.

Drainage basins function as essential geomorphic entities crucial for hydrological management and sustainable utilization of natural resources. Geological, morphological, topographical, and climatic elements are pivotal in molding fluvial systems, drainage patterns, and their density. Discrepancies in these environmental conditions frequently lead to variances in the morphometric attributes of drainage basins and the corresponding fluvial systems. (Yahya et al., 2016).

The drainage system inside a river basin is quantitatively described by the morphometric analysis, offering valuable insights into basin characteristics (Strahler, 1964). A drainage basin represents the 3D land area where surface water from various forms of precipitation, meets to a single point or joins another water body before ultimately leaving the basin through surface runoff, through-flow, or groundwater flow. The basin's storage system comprises vegetation interception, surface storage, transpiration, evaporation, soil moisture, and groundwater. Physical, meteorological, and human factors primarily govern the behavior of drainage basins. Physiographic characteristics can be correlated with various hydrological phenomena (Rastogi & Sharma, 1976). Other factors influencing basins include elevation, gradient, rock, soil, drainage density, rainfall intensity, antecedent conditions, rates of evapotranspiration, urbanization, deforestation, afforestation, and water withdrawal (Adhikari, 2020).

Watershed prioritization is categorizing different watersheds according to their importance for adopting management and conservation actions. Remote sensing and Geographic Information System (GIS) have arisen as important tools for morphometric analysis and the creation of regional hydrological models, particularly in data-scarce circumstances such as India. These strategies are quite useful for prioritizing watersheds. Morphometry enables quantitative drainage basin analysis, providing critical information for watershed characterization.

The analysis of drainage basin characteristics encompasses three important aspects: linear, areal, and relief aspects. In this study, we aim to assess the flood susceptibility of the Warana River by analyzing various morphometric aspects of the basin. By investigating the aforementioned parameters, this study seeks to evaluate the flood vulnerability of the Warana River and provide valuable insights into the basin morphology for effective flood management planning.

2. Study Area

The study area focuses on the Warana basin, which encompasses the Warana River and its surrounding drainage region (Figure 1). The Warana basin is located in the Sangli and Kolhapur districts of Maharashtra, India. It is situated in the western part of the country and is part of the larger Krishna River basin. The Warana basin covers an extensive area of approximately 2085 km^2. It is characterized by diverse physiographic features, including hilly regions, plateaus, and plains. The basin exhibits a varied topography, with elevations ranging from 914 meters above sea level at its highest point on Prachitgad in the Sahyadri mountain range, to lower elevations as it flows towards its confluence with the Krishna River.

The river originates from the Warana Dam and initially flows in a northwest-to-southeast direction before turning eastward. It passes through the scenic Warana valley, which is known for its picturesque landscapes and agricultural activities. The Warana River plays a dominant role in supporting the local economy by providing water for irrigation and sustaining various industries along its course. The basin is influenced by a monsoonal climate, with the majority of the rainfall occurring during the south-west monsoon season from June to September. The high rainfall intensity, coupled with the geomorphological characteristics of the basin, makes it prone to flooding. The Warana River, in particular, is susceptible to periodic flooding, posing challenges for the local communities and infrastructure in the region.

Geologically, the Warana Valley is situated in the north-western part of the Deccan Trap, a volcanic basaltic rock formation. The topography of the valley is highly diverse and exhibits a complex landscape with various landforms. The valley itself lies in a transitional zone between the Konkan area to the west and the Deccan Plateau to the east. The west side region of the Warana Valley is characterized by steep slopes and rugged terrain, while the eastern region gradually becomes flatter. As the river flows from its origin, the basin widens, particularly in the Hatkanagale and Shirol tehsils. The soil composition in most parts of the basin is predominantly red alluvial soil. The depth of the Warana River varies throughout its course. In the upper region of the basin, closer to its origin, the river tends to have greater depth. However, the river gradually becomes shallower as it progresses downstream towards the middle and later portions of the basin. These geological and topographical features of the Warana Valley influence the hydrological behavior of the river basin. The complex topography with red alluvial soil can affect the water retention and runoff patterns within the basin. Understanding these geomorphic characteristics is essential for evaluating the flood susceptibility of the Warana River basin and developing appropriate flood management strategies.

3. Database and Methods

In order to accomplish the research objectives, data for the study was obtained from the Alaska Satellite Facility data portal, which provides remotely sensed imagery of the Earth. Specifically, the study utilized the "Hi-Res Terrain Corrected (12.5 Meter Resolution) 2011" data from the ALOS PALSAR satellite, which was a Digital Elevation Model (DEM) dataset. This dataset was selected for calculating various morphometric parameters and was also used for watershed delineation and analyzing other morphometric aspects (Figure 2).

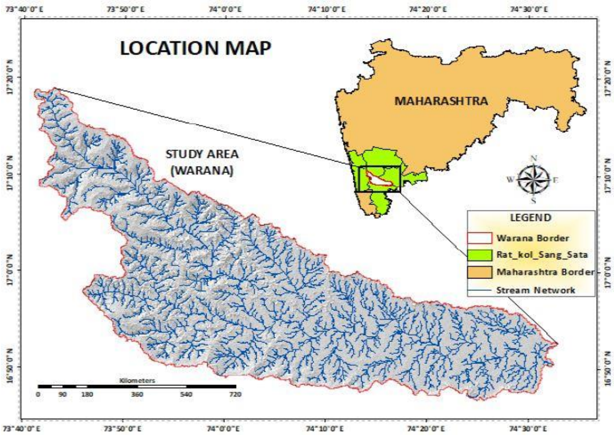

Figure 1. Study Area

A total 22 morphometric parameters were considered to depict the Warana River basin and prioritize its sub-watersheds for susceptibility to flash floods (Table 1). Basic parameters were directly measured from the DEM using GIS techniques. The ArcSWAT tool in ArcGIS software was utilized to subdivide the Warana River into sub-watersheds. Other morphometric parameters were intended using mathematical formulas specified in Table 1.

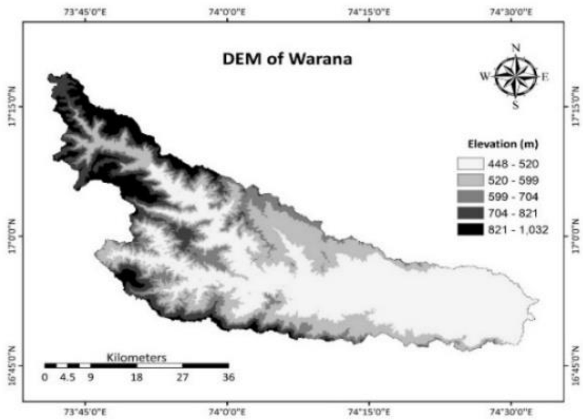

Figure 2. DEM of Warana River Basin

The Morphometric Ranking, specifically the Total Rank approach, was employed for prioritizing the subwatersheds (Patel et al., 2012; Mutawakil et al., 2021). Each morphometric parameter was assigned to a specific rank group, representing different degrees of flood risk. For instance, Rank 1 indicated a very low possibility of flood risk, while higher ranks denoted increasing degrees of risk. 12 parameters were selected to assess the susceptibility of sub-watersheds to flooding. Eight parameters exhibited a direct relationship with flood risk, meaning that higher parameter values indicated higher risk degrees. Conversely, four parameters showed an inverse relationship with flood risk, with higher parameter values indicating lower risk degrees (Mutawakil et al., 2021). The systematic flow of the research methodology is shown in Figure 3.

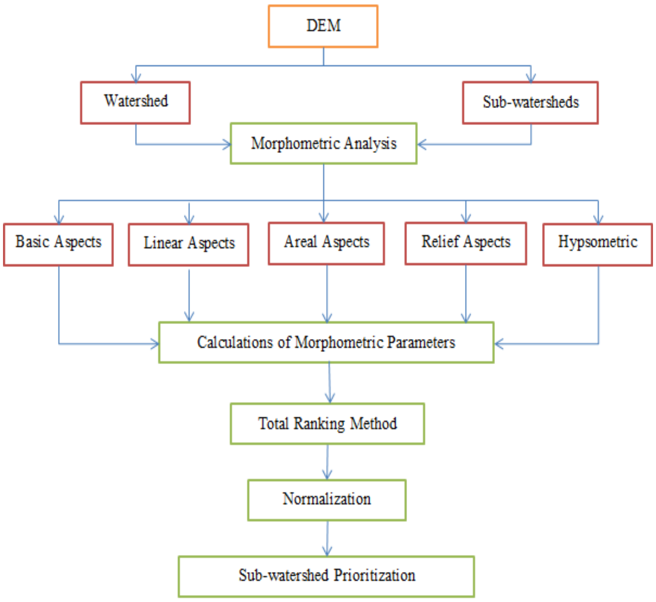

Figure 3. Research Methodology Flowchart

Table 1. Parameters used for the morphometric analysis

Morphometric parameters	Formula	Reference
Basic		
1. Basin area (A)	Plan area of the watershed (km^2)	Horton (1945)
2. Basin perimeter (P)	Perimeter of the watershed (km)	Horton (1945)
3. Basin length (Lb)	Length of the basin (km)	Horton (1945)
4. Stream order (U)	Hierarchical rank	Strahler (1952), Farhan, Anbar, Enaba, and Al-Shaikh (2015)
5. Total number of streams (Nu)	Total no. of streams of all orders	Strahler (1952)
6. Stream length (Lu)	Length of the stream (km)	Horton (1945)
7. Mean stream length (Lsm)	Lsm = Lu/Nu (km) where, Lu = total stream length of all orders Nu = total no. of stream segments of order "u"	Horton (1945)
8. Stream length ratio (RL)	RL = Lu/Lu − 1 where, Lu − 1 = the total stream length of its next lower order	Horton (1945)
Linear		
9. Bifurcation ratio	(Rb) Rb = Nu/Nu + 1, where Nu + 1 = no. of segments of the next higher order	Strahler (1957)
10. Mean bifurcation ratio (Rbm)	Rbm = average of the bifurcation ratio of all orders	Strahler (1957)
11. Drainage density (Dd)	Dd = Lu/A, where Lu = total stream length of all orders (km) A = area of the watershed (km^2)	Horton (1945
12. Length of overland flow (Lo)	Lo = 1/(2*Dd), where, Dd = drainage density	Horton (1945)
13. Stream frequency (Fs)	Fs = Nu/A, where Nu = total no. of streams of all orders A = area of the basin (km^2)	Horton (1945)
Shape		
14. Elongation ratio (Re)	Re = 1.128*(A^0.5)/Lb, where A = area of the basin (km2) Lb = basin length (km)	Strahler(1957)
15. Circularity ratio (Rc)	Rc = 4 × π × A/P2 , where π = 3.14, A = area of the basin (km^2) P = perimeter (km)	Schumm (1956)
16. Shape factor (Bs)	Bs = Lb 2 /A, where Lb = basin length (km) A = area of the basin (km2)	Miller (1953)
Relief		
17. Basin relief (H)	H = h – h1, where h = maximum height (m) h1 = minimum height (m)	Horton (1945)
18. Relief ratio (Rr)	Rr = H/Lb, where H = total relief (km) Lb = basin length (km)	Malik et al. (2011)
19. Relative relief ratio (Rv)	H/P, where H = total relief (km), P= perimeter of the basin (km)	Schumm (1956)
20. Basin slope (Sw)	H/Lb*60, where H = total relief (km), Lb = basin length (km)	Melton (1957)
21. Ruggedness number (Rn)	Rn = Dd*H, where H = basin relief (km), Dd = drainage density	Farhan and Anaba (201
Hypsometric		

Following morphometric ranking, the cumulative values for individual sub-watersheds were aggregated to assess their vulnerability to flash floods. Utilizing a methodology akin to Farhan & Anaba (2016), a basic formula was employed to determine the length of intervals, calculated as (Max - Min) / 4. Each parameter's values were then divided into four intervals. The cumulative ranks of morphometric parameters were subsequently normalized between 0 (indicating the lowest rank) and 1 (suggesting the highest rank) to derive the flash flood susceptibility index for each sub-watershed. Comparable parameter values were allotted analogous rankings. Ultimately, a flood priority map was crafted by categorizing the findings into four susceptibility levels: low, moderate, high, and very high priority.

The equation for generalization - (X-Xmin)/ (Xmax-Xmin)

where, X is the total rank value.

4. Results and Discussion

4.1 Morphometric Analysis

The Warana River basin was separated into 13 sub-watersheds using the ArcSWAT tool in ArcGIS (Figure 4). The study area exhibited high relief, with elevations reaching up to 1,032 meters. The Warana River basin was classified as a sixth order basin, covering area of 2085 km^2, with a length of 104.75 km and a perimeter of 460 km. The basin consisted of a total of 2665 streams, with first-order streams contributing to nearly 51% of the total. The morphometric analysis results for the entire basin can be found in Table 2, while those for the sub-watersheds are presented in Table 3. The prevalent drainage pattern identified within the basin was dendritic, a characteristic typically linked with uniform impermeable rock formations. This pattern arises when the underlying geological structure offers consistent resistance to erosion (Gizachew and Berhan, 2018).

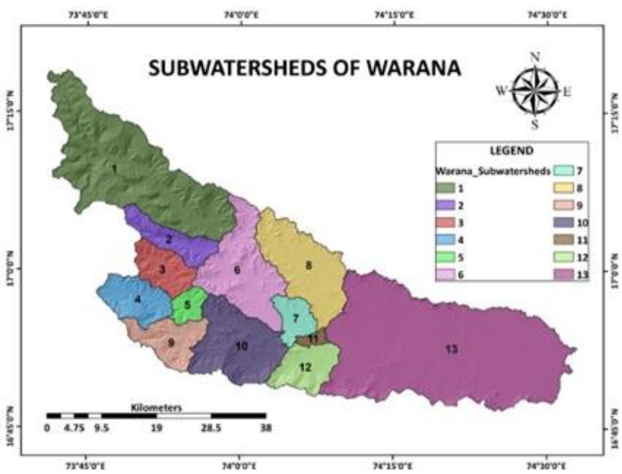

Figure 4. Delineated Sub-watersheds of the Warana River basin

Table 1. Morphometric Parameters of Warana River Basin

Par. No.	Morphometric parameter							
Basic								
1.	(A) (km^2)	2085						
2.	(P) (km)	460						
3.	(Lb) (km)	104.75						
4.	(U)	6	I	II	III	IV	V	VI
5.	(Nu)	2665	1337	601	346	126	147	108
6.	(Lu) (km)	2343.92	1286.81	546.97	252.01	86.64	92.29	79.18
7.	(Lsm) (km)	0.88	0.96	0.91	0.73	0.69	0.62	0.73
8.	(RL)			II/I	III/II	IV/III	V/IV	VI/V
				0.43	0.46	0.34	1.07	0.86
Linear								
9.	(Rb)		I/II	II/III	III/IV	IV/V	V/VI	
			2.22	1.74	2.75	0.86	1.36	
10.	(Rbm)	1.79						
11.	(Dd) (km)	1.12						
12.	(L) (km)	0.56						
13.	(Fs)	1.28						
Shape								
14.	(Re)	0.49						
15.	(Rc)	0.12						
16.	(Bs)	5.26						
Relief								
17.	(H) (m)	584m						
18.	(Rr)	0.006						
19.	(Rv)	0.00127						
20.	(Sw)	0.334						
21.	(Rn)	0.656522						
Hypsometric								
22.	(HI)	0.5						

4.1.1 Basic parameters

Basin area (a) and basin perimeter (P)

The watershed area can directly replicate the total volume of water. The area of the Warana basin was 2085 km^2 and the area of sub-watersheds ranges from 10.67 km^2 for SW 11 to 699.17 km^2 for SW 13 (Table 3). The P serves as an outer boundary delineating the extent of a watershed, offering insights into its shape and size. A notable correlation (r = 0.89) was established between the area of sub-watersheds and their respective perimeters (Figure 5a). This correlation highlights a direct relationship, indicating that as the area of the basin increased, so did its perimeter.

Basin Length (Lb)

Lb, defined as the longest distance within a basin from the catchment area to the point of confluence, serves as a crucial parameter in assessing watershed shape and relative relief (Gregory & Walling, 1973; Prabhakaran & N. Jawahar Raj, 2018). Across all 13 sub-watersheds, Lb ranged from 6.56 km for SW 11 to 43.65 km for SW 13. The correlation between basin length and basin slope is illustrated in figure 5b, revealing a strong negative correlation (r = -0.77). Conversely, the relationship between basin length and stream length demonstrates a strong positive correlation (r = 0.9), as depicted in figure. 5c.

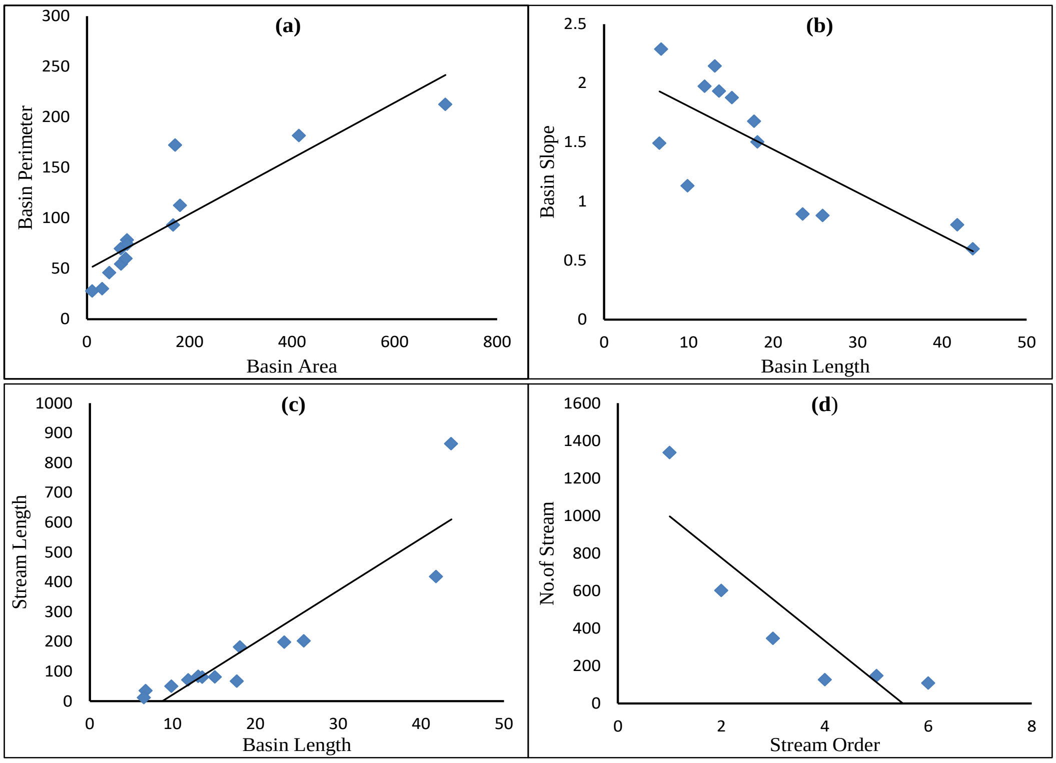

Figure 5. Basin area vs. basin perimeter (a), basin length vs. basin slope (b), basin length vs. stream length (c), and stream order vs. number of streams (d)

Stream order (U), total number of streams (Nu)

U delineates the hierarchical arrangement of individual stream segments within a drainage network (Ali & Khan 2013). In this study, stream orders were classified up to the sixth order, following the methodology proposed by Strahler (1964). Across all 13 sub-watersheds, the number of streams amounted to 2665, with first-order streams comprising 51% of this total, totaling 1337 streams. This distribution aligns with Horton's principle (1932), indicating a decrease in stream number with an rise in stream order, as illustrated in figure 5d. Among the 13 sub-watersheds, SW 13 boasted the highest number of streams (Nu = 912), while SW 11 exhibited the lowest (Nu = 13).

Stream length (Lu)

The Lu within the Warana basin demonstrates a consistent decrease as stream order increases, exhibiting a strong negative correlation (r = -0.85) (Figure 6, 7a). This observation aligns with Horton's second law of stream length (1945), which posits that the average length of streams of each order in a drainage basin tends to approximate a direct geometric ratio. Specifically, first-order streams spanned a length of 1286.81 km, constituting 55% of the total length, while sixth-order streams accounted for only 3.4%. Longer streams are indicative of a watershed's potential to produce more runoff and less infiltration (Strahler, 1952).

Conversely, a strong positive correlation (r = 0.99) was noted between stream length and basin area, indicating that an increase in stream length resembles to an increase in basin area (Figure 7b). The RL, defined as the ratio of the mean length of one order of stream segments to the next lower order (Horton, 1945), ranges from 0.43 to 0.86 within the Warana River basin. This variation in RL values across different stream orders attributed to disparities in slope and topography.

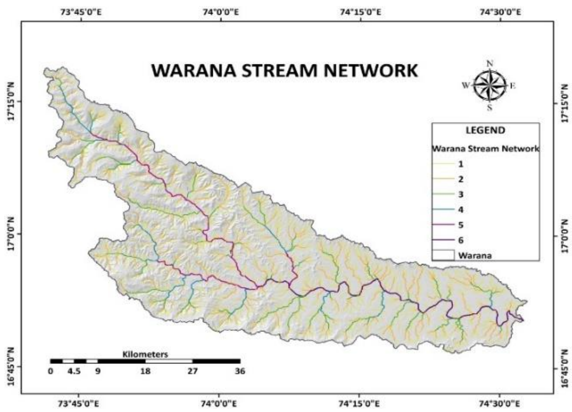

Figure 6. Stream Network of Warana River Basin

4.1.2 Linear parameters

Drainage density (Dd)

Dd is defined as the ratio of total stream length within a particular basin to the total area of the basin (Strahler, 1964). It serves as an indicator of basin drainage efficiency, with well-drained basins typically exhibiting lower Dd values around 0.73, while poorly-drained basins have higher values nearing 2.74 (Horton, 1945). In the case of the Warana basin, the Dd value stands at 1.12, with the lowest Dd values observed in SW 1 & 2 and the highest in SW 13. Higher drainage density is often allied with basins characterized by weak and resistant subsurface material, sparse vegetation cover, and significant relief (Strahler, 1964). A moderate negative correlation (r = -0.56) was identified between drainage density and basin relief (Figure 7c).

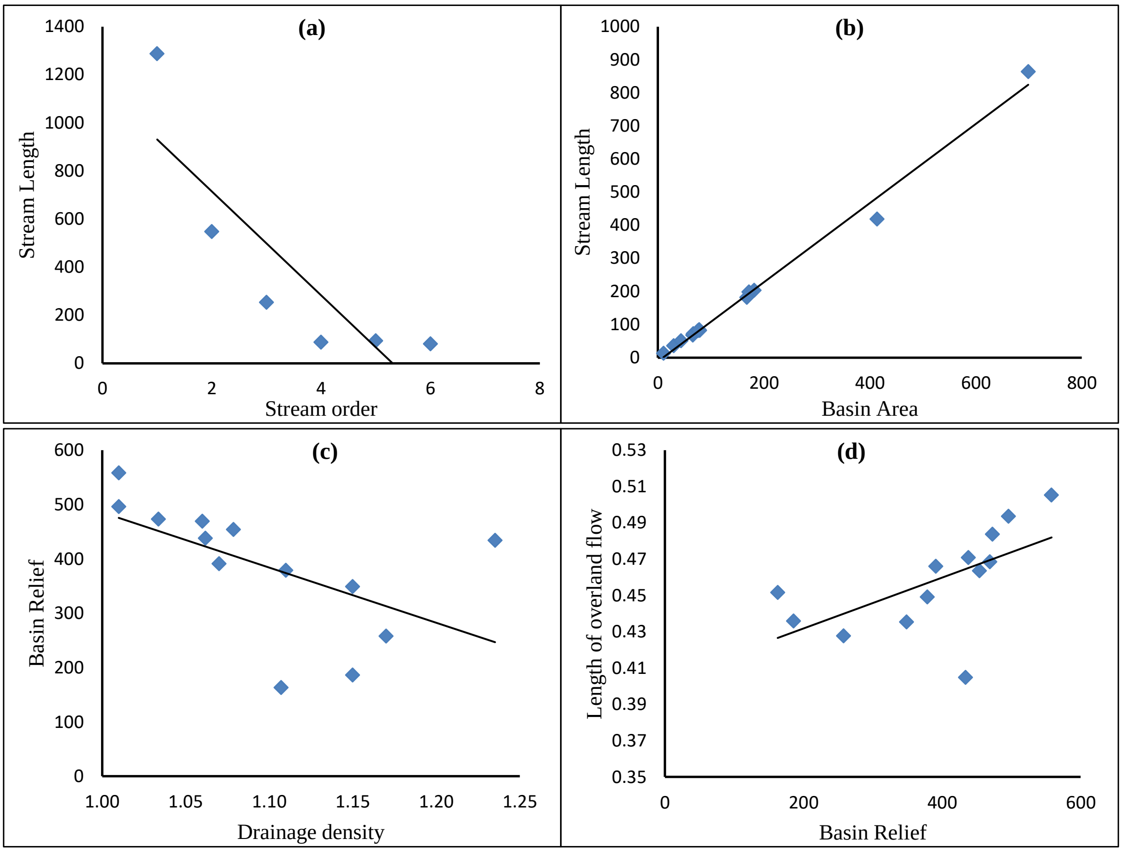

Figure 7. Stream order vs. stream length (a), basin area vs. stream length (b), drainage density vs.basin relief (c), and basin relief vs. length of overland flow (d)

Length of overland flow (Lo)

The Lg represents the distance water travels over the ground before it converges into the main stream, influencing the hydrological and physiographic evolution of a drainage basin (Horton, 1945). For the Warana basin, the Lg value is 0.56, varying from 0.40 for SW 13 (exhibiting high susceptibility to flash flood) to 0.51 for SW 1 (showing low susceptibility to flash flood). A moderate positive link (r = 0.6) was observed between the length of overland flow and basin relief (Figure 7d).

Stream frequency (Fs)

Fs, a measure of the total number of stream sections across all orders relative to the basin area (Horton, 1945), for the Warana basin stands at 1.28. This metric ranges from 1.18 for SW 3 to 1.69 for SW 7. These values indicate a propensity for low surface runoff and heightened infiltration of surface water within the basin. Moreover, stream frequency positively correlates with drainage density, suggesting that as the stream population increases, so does the drainage density (Adhikari, 2020).

Bifurcation ratio (Rb) and mean bifurcation ratio (Rbm)

As per Schumm (1956), the Rb represents the ratio of stream sections of a particular order to those of the subsequent higher order. In the case of the Warana basin, Rb ranges from 0.86 to 2.75. This range suggests that the basin is relatively flat or rolling, with less structural disturbance. The Rbm serves as an indicator of the stream network's distribution (Mesa, 2006; Mutawakil et al., 2021). For the study region, the Rbm value is 1.79, indicating a geologically controlled and structurally less disturbed watershed, or the absence of significant distortion in drainage patterns (Soni, 2017).

4.1.3 Shape parameters

Elongation ratio (Re)

The Re compares the diameter of a circle with the same area as the drainage basin to its longest length (Schumm, 1956). A value below 0.8 typically signifies high relief with an elongated shape, while values near 1.0 suggest very low relief with a circular shape (Magesh et al., 2013; Adhikari, 2020). For the Warana basin, the Re value is 0.49, indicating a basin with high relief and steep slopes. SW 5, with an Re of 0.91, demonstrates low sensitivity to flooding due to its low relief, whereas SW 2 (Re = 0.52) suggests higher susceptibility to flooding due to its high relief. There exists an inverse correlation between Re and flooding susceptibility (Mutawakil et al., 2021).

Circularity ratio (Rc)

Rc compares the watershed area to the region of a circle with the same edge as the watershed (Miller, 1953). An Rc value of 1 designates a perfectly circular basin, while values between 0.4 and 0.5 suggest a substantially elongated shape with highly permeable homogeneous geological material (Adhikari, 2020). For the Warana basin, the Rc value is 0.12, suggesting that the basin is at a mid-stage of topographical maturity. All sub-watersheds within the Warana exhibit strong elongation. SW 8 has the lowest Rc (0.07), while SW 5 has the highest (0.42), indicating a high potential for flooding.

Shape factor (Bs)

Bs is determined by the ratio among the square of the main flow path and the watershed area (Miller, 1953). For the Warana basin, the Bs value stands at 5.26, varying from 1.53 for SW 5 to 4.78 for SW 2. These Bs values indicate an elongated shape for the sub-watersheds, consistent with the circularity ratio mentioned earlier. Lower shape factor values suggest high relief and steep slopes, factors that can exacerbate flooding. Bs exhibits an inverse relationship with flooding (Mutawakil et al., 2021). Consequently, sub-watersheds 3, 4, 5, 7, and 10, characterized by low Bs values, were assigned the highest rank (4), while sub-watersheds 1, 2, and 11, with high Bs values, were assigned the lowest rank.

4.1.4. Relief Parameters

Basin relief (H), relief ratio (Rr), relative relief ratio (Rv)

H represents the height contrast between the uppermost and lowermost points within a basin, crucial for understanding landform and drainage development, water flow patterns, permeability, and erosion (Magesh et al., 2011; Mutawakil et al., 2021). The total relief of the Warana basin is 584 m, indicating moderate conditions for both penetration and surface runoff. SW 11 exhibits the lowest H value (163 m), while SW 1 has the highest (558 m).

The Rr of a basin, defined as the ratio of total relief to the longest dimension parallel to the prime drainage line (Schumm, 1956), reflects the slope and relief characteristics. The Warana basin has a Rr of 0.006, suggesting very low sensitivity to flash flood occurrences. SW 4 & 5 demonstrate relatively higher sensitivity (Rr = 0.04) compared to SW 1, 6, 8 & 13 (Rr = 0.01), which are less sensitive.

Rv, the ratio of relief to the boundary of the watershed (Melton, 1957), is another indicator of flood sensitivity. Warana's Rv is 0.00127, ranging from 0.002 for SW 8 & 13 (low sensitivity) to 0.009 for SW 5 (high sensitivity). Rv exhibits a direct relation to flooding, thus SW 2, 3, 5, and 12 with higher Rv values were assigned the highest rank (4), while SW 1, 6, 8, and 13 with lower Rv values received the lowest rank.

Basin slope (Sw)

Sw plays a significant role in determining surface runoff amount and speed, with higher slopes typically resulting in rapid runoff and reduced infiltration capacity (Bisht et al., 2018). The Warana basin exhibits a slope of 0.334 degrees, considered low and indicative of a low potential for flash floods. SW 5, with a slope of 2.29 degrees, emerges as relatively more prone to flooding, while SW 13 shows the least sensitivity. Basin slope demonstrates a direct relationship with flash floods.

Ruggedness number (Rn)

Rn serves as a metric for quantifying the surface unevenness of a basin's terrain (Selvan et.al., 2011). Elevated drainage density and relief contribute to higher Rn values, indicative of both steep and extensive slopes (Strahler, 1957). The Rn value for the Warana basin is 0.66, suggesting a terrain with relatively plain topography and low sensitivity to floods and erosion. Across sub-watersheds, Rn ranges from 0.18 for SW 12, indicating low sensitivity to flooding, to 0.56 for SW 1, indicating relatively higher sensitivity to flooding. Additionally, a strong positive association (r = 0.98) exists between basin relief and ruggedness number.

Table 2. Morphometric Parameters of Sub-watersheds of Warana

SW	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
A	413.66	66.08	66.74	78.18	30.04	181.7	43.8	172.11	78.82	168.21	10.67	75.65	699.17
P	181.48	69.68	54.45	78.18	30.04	112.53	45.9	172.11	73.98	93.1	27.83	59.93	212.53
Lb	41.81	17.77	11.9	13.13	6.77	25.87	9.88	23.52	15.13	18.15	6.56	13.6	43.65
Lu	417.99	66.95	71.6	83.43	35.13	202.26	50.24	197.64	81.48	181.43	11.81	80.33	863.63
Nu	502	86	79	103	43	237	74	204	113	219	13	93	912
Dd	1.01	1.01	1.07	1.06	1.17	1.11	1.15	1.15	1.03	1.08	1.11	1.06	1.24
Lo	0.51	0.49	0.47	0.47	0.43	0.45	0.44	0.44	0.48	0.46	0.45	0.47	0.4
Fs	1.21	1.3	1.18	1.32	1.43	1.3	1.69	1.19	1.43	1.3	1.22	1.23	1.3
Re	0.55	0.52	0.77	0.76	0.91	0.59	0.76	0.63	0.66	0.81	0.56	0.72	0.68
Rc	0.16	0.17	0.28	0.16	0.42	0.18	0.26	0.07	0.18	0.24	0.17	0.26	0.19
Bs	4.23	4.78	2.12	2.2	1.53	3.68	2.23	3.21	2.9	1.96	4.04	2.45	2.73
Rr	0.01	0.03	0.03	0.04	0.04	0.01	0.02	0.01	0.03	0.03	0.02	0.03	0.01
Rv	0.003	0.007	0.007	0.006	0.009	0.003	0.004	0.002	0.006	0.005	0.006	0.007	0.002
Sw	0.8	1.68	1.97	2.14	2.29	0.88	1.13	0.89	1.88	1.5	1.49	1.93	0.6
Rn	0.56	0.5	0.42	0.5	0.3	0.42	0.21	0.4	0.49	0.49	0.18	0.47	0.54
HI	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
H	558	496	391	469	258	379	186	349	473	454	163	438	434

4.1.5 Hypsometric Parameters

Hipsometric Integral (HI)

HI serves as a vital tool for analyzing topography, offering insights into the interplay between factors such as tectonic uplift, climate, lithology, and erosion (Pavano et.al., 2018; Mutawakil et al., 2021). The erosion cycle can be delineated into three stages: the young stage (HI > 0.6), characterized by high susceptibility to erosion; the equilibrium to mature stage (HI = 0.3 to 0.6); and the old stage (HI < 0.3) (Mehar et al., 2018). The Warana basin exhibits an HI value of 0.5, consistent across all sub-watersheds. This consistent HI value indicates the uniform development of various sub-watersheds, all residing in their equilibrium erosion stage.

4.1 Watershed prioritization of the Warana

The prioritization process involved evaluating 12 parameters to identify sub-watersheds requiring immediate attention for flash flood management and planning. Eight parameters directly related to runoff were ranked higher as their values increased, indicating a greater potential for flooding. Conversely, the length of overland flow, elongation ratio, shape factor, and hypsometric integral, which inversely related to runoff, were ranked higher with lower values, indicating a higher flood risk.

Using this methodology, ranks ranging from 1 to 4 were assigned based on the relationship of morphometric parameters with flash floods. For instance, SW 13 received the highest rank (4) due to its high drainage density directly related to flash floods, while SW 2–12 received the lowest rank (1). Similarly, SW 7, exhibiting high stream frequency, received the highest rank (4) due to its direct relationship with flood susceptibility.

Sub-watersheds with Re in the range of 0.52–0.59 (SW 1, 2, 6, and 11) received the highest rank (4) due to their inverse correlation with flooding, while SW 5 with Re 0.91 was ranked lowest (1). SW 5, with the highest Rc, indicating a high flood risk, received the lowest rank (1), while SW 1 and 8, with the lowest Rc, were ranked higher. Similarly, sub-watersheds with lower values of Bs received higher ranks due to the inverse relationship with flooding, while those with higher values received lower ranks. The same trend was observed for Rv, Sw, and Rn, with higher values indicating higher flood risk and consequently receiving lower ranks. Further, the total rank method was applied for each sub-watershed based on the figured morphometric parameters, which were then normalized and classified into 4 classes of flash flood susceptibility. These classes were very high (0.75–1), high (0.5–0.75), moderate (0.25–0.5), and low (0–0.25) priorities (Table 4).

Table 3. Calculation of ranks for morphometric parameters and the total rank value for the sub-watersheds in the Warana for flash floods

SW	A	Dd	Lo	Fs	Re	Rc	Bs	Rr	Rv	Sw	Rn	Total Rank	Normalization	Prioritized Rank	Priority
1	3	1	1	1	4	1	1	1	1	1	4	19	0	1	Low
2	1	1	1	1	4	2	1	3	4	3	4	25	0.428571	5	Moderate
3	1	2	2	1	2	3	4	4	4	4	3	30	0.785714	9	Very High
4	1	2	2	2	2	2	4	4	3	4	4	30	0.785714	9	Very High
5	1	3	4	2	1	4	4	4	4	4	2	33	1	10	Very High
6	1	2	3	1	4	2	2	1	1	1	3	21	0.142857	3	Low
7	1	3	3	4	2	3	4	2	2	2	1	27	0.571429	7	High
8	1	3	3	1	3	1	2	1	1	1	3	20	0.071429	2	Low
9	1	1	1	2	3	2	3	4	3	4	4	28	0.642857	8	High
10	1	2	2	1	2	2	4	3	2	3	4	26	0.5	6	High
11	1	2	3	1	4	2	1	3	3	3	1	24	0.357143	4	Moderate
12	1	1	2	1	2	3	3	4	4	4	3	28	0.642857	8	High
13	4	4	4	1	3	2	3	1	1	1	4	28	0.642857	8	High

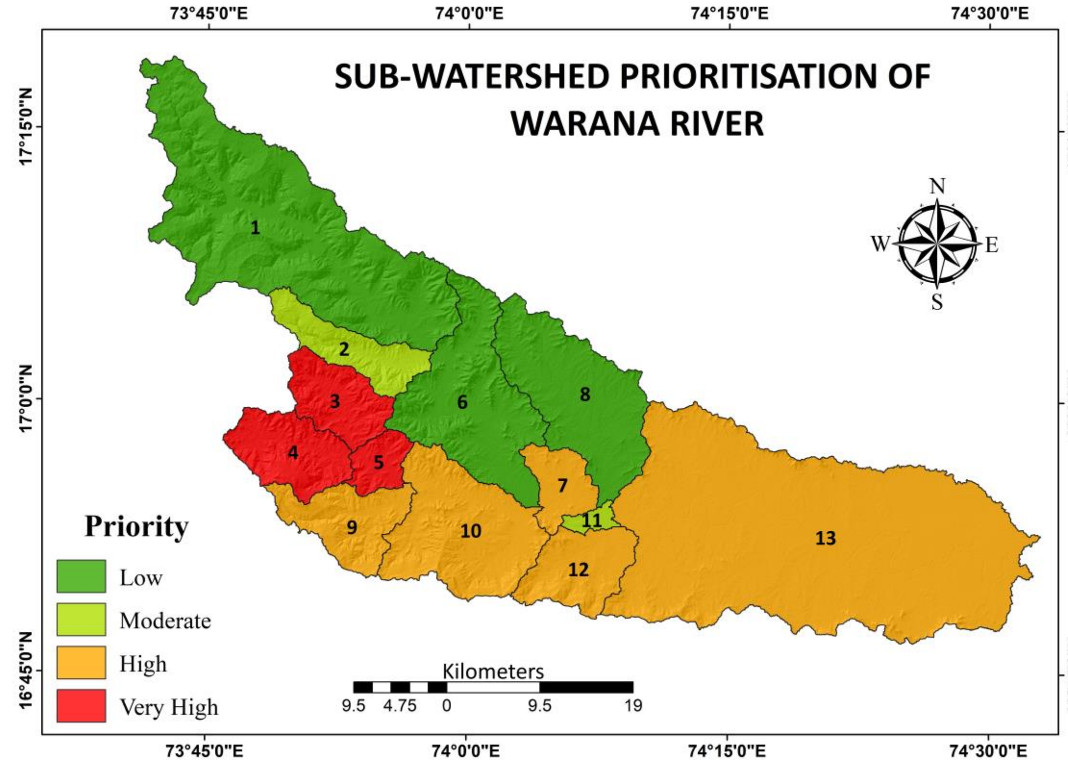

Figure 8. Classification of sub-watersheds according to flash flood susceptibility

The ultimate susceptibility flash flood map, depicted in figure 8, highlights the distribution of sub-watersheds across different priority classes based on their susceptibility to flash floods. Three sub-watersheds (SW 3, 4, 5) located in the western part of the basin were categorised as very high priority, encompassing approximately 8.4% of the total basin area. These sub-watersheds are extremely susceptible to flash floods and require immediate attention. Five sub-watersheds (SW 7, 9, 10, 12, 13), covering 51.1% of the total basin area, were categorized as high priority. This classification indicates a significant susceptibility to flash floods and necessitates prompt management measures. Only two sub-watersheds (SW 2 & 11) were classified as moderate priority, constituting approximately 3.7% of the total basin area. These sub-watersheds exhibit a moderate susceptibility to flash floods. Lastly, the low-priority class includes three sub-watersheds (SW 1, 6, 8), covering around 36.8% of the total basin area. These sub-watersheds have a lower susceptibility to flash floods compared to others. Combining the very high and high priority class sub-watersheds, approximately 59.5% of the entire basin area is considered at risk of flash floods. This emphasizes the importance of focusing efforts and resources on mitigating the risk and managing flash flood occurrences in these areas.

Conclusions

The morphometric analysis and prioritization of the Warana River basin underscore the significant vulnerability of a considerable portion (59%) of its area to flash floods. This underscores the urgent need for proactive measures to safeguard lives and agricultural assets from potential flooding events. Key parameters influencing flooding in the basin include the relief ratio, relative relief ratio, basin slope, and ruggedness number.

The insights gleaned from this study, coupled with the flood susceptibility map generated, offer invaluable resources for disaster planners and decision-makers. They enable targeted identification and mitigation of high-risk areas through the implementation of appropriate preventive measures. These measures could encompass initiatives such as afforestation, hillside terracing, and the construction of floodways, dams, and retention ponds. Given the significance of agriculture in the region, particular attention should be paid to mitigating flood risks to this sector.

Moreover, it is advisable to explore water resource development options, such as constructing a downstream dam in areas highly susceptible to flash floods. Such infrastructure could not only mitigate flood risks but also facilitate efficient surface water utilization for irrigation and groundwater aquifer recharge.

By leveraging these recommendations and implementing proactive measures, stakeholders can significantly enhance the resilience of the Warana River basin community against the adverse impacts of flash floods, safeguarding lives and livelihoods while promoting sustainable development.The integration of morphometric analysis with geospatial techniques has proven to be a valuable approach to assessing sub-watershed properties related to flooding management. This study emphasizes the importance of utilizing such tools to enable responsible authorities to take appropriate measures and devise effective prevention, protection, and mitigation plans to reduce the impact of flash floods in the Warana basin and ensure the overall safety and well-being of the region.

Conflict of Interest

The authors confirm that there is no conflict of interest.

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