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Geospatial Flood Susceptibility Mapping for Human Safety and Urban Risk Reduction in Ras Al Khaimah, UAE

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ABSTRACT: Flash floods pose a serious threat to human safety, urban infrastructure, and sustainable development, particularly in regions exposed to intense rainfall. Identifying areas that are more susceptible to flooding is therefore important for reducing potential damage and supporting effective disaster management. This study assesses flood susceptibility across drainage basins in Ras Al Khaimah, United Arab Emirates, where major flash flood events were reported in 2010, 2011, 2016, 2022, and 2023. Geospatial analysis of basin morphometric characteristics was combined with the Topographic Position Index (TPI) and Topographic Wetness Index (TWI) to examine terrain conditions and identify areas with varying levels of flood susceptibility. The results indicate that drainage basins 2, 6, and 8 have very high flood susceptibility, whereas basins 1, 3, 4, and 9 show moderate susceptibility. Basins 5 and 7 fall within the low-susceptibility category. The resulting susceptibility map provides a spatial overview of areas that may require greater attention during flood-risk planning. The study also examines the relationship between urban development and flood-prone areas, highlighting the importance of considering terrain characteristics and settlement patterns in land-use planning. This integrated geospatial approach can support the identification of vulnerable locations, guide infrastructure planning, and strengthen local flood preparedness. The findings provide a useful basis for further research linking environmental hazards with human exposure and health risks in flood-prone urban regions.

1. INTRODUCTION

Flood susceptibility refers to the probability of an area which will het affected by floods due to both man-made and natural processes. These kinds of processes are governed by a complex interaction of physical, hydrological and environmental factors that are useful in controlling runoff, water accumulation and water flow (Beven, 2012; IPCC, 2021). Some of the major factors which contribute flood susceptibility are topography, landuse pattern, type pf soil, rainfall, type of vegetation, etc. In addition to these human activities particularly the urbanization and deforestation are major contributors which increase the probability of flood susceptibility in a region (Merz et al., 2007; IPCC, 2014). Areas situated in low-lying terrains especially nearby the floodplains, coastal zones and wadis are prone to inundation due to their geomorphological and hydrological characteristics (Smith, 2013).

During the recent, flooding is widely recognized as one of the most frequent and damaging natural hazards across the globe which lead to loss of life, damage to basic livelihoods and degradation of environmental resources (UNDRR, 2019). In recent decades, the increasing frequency and intensity of extreme precipitation events, coupled with rapid land-use change, have intensified flood risks in many regions (Hirabayashi et al., 2013; Winsemius et al., 2016). In general, flood management mostly

depend on structural measures such as dams, levees and floodwalls. However, due to the change in climatic conditions, these approaches have proven insufficient and making us lead to shift toward integrated and risk-based flood management strategies. This helps in understanding the flood risk and to support in more effective planning (Kundzewicz et al., 2014).

In arid and semi-arid environments, flood events are often short-duration. These kinds of flash flooding activities are mostly due to sudden high-intensity rainfall which triggers quick surface runoff, particularly in regions with lesser vegetation, shallow soils and limited infiltration capacity. The northern part of the United Arab Emirates (UAE), especially the Ras Al Khaimah region, has experienced persistent flood events over the past decade, notable occurrences in 2010, 2011, 2016, 2022, and 2023 (Elhakeem, 2017 and public reporting). These kinds of events might mostly cause significant disruption to the settlements and will restrict normal transportation and infrastructure usage, The geomorphological setting of the region also play a major phenomenon for flood related activities in any region ((Kaliraj et al., 2017; Logesh et al., 2021). The Ras Al Khaimah region is characterized by rugged mountains, interconnected wadi systems and rapidly expanding urban areas which creates conditions conducive to flash flooding. Furthermore, ongoing land-use changes and infrastructure development have also altered the natural drainage pathways, increasing the likelihood of localized flooding. Therefore, a comprehensive assessment of flood susceptibility in this region is essential to support sustainable urban development, improve disaster preparedness and enhance resilience against future hydrometeorological extremes.

Given the increasing occurrence of flood events and the complex interplay of contributing factors, there is a critical need for systematic and spatially explicit assessment of flood susceptibility in the study region. Such studies not only improve the accuracy of flood risk assessments but also provide valuable insights for planners and decision-makers. In this context, the present study aims to evaluate flood susceptibility in the Ras Al Khaimah region by integrating geospatial datasets and analytical techniques to identify flood-prone zones. The outcomes of this study are expected to support informed land-use planning, enhance disaster risk reduction strategies, and contribute to the development of resilient infrastructure in flood-vulnerable regions.

2. MATERIALS AND METHODS

2.1 Study Area

Ras al Khaimah is one of the seven emirates that make up the United Arab Emirates (UAE), and is situated on the northern coast of the Arabian Peninsula. It is bordered by the Gulf of Oman to the east, the emirate of Fujairah to the southeast, and the emirates of Sharjah and Umm al-Quwain to the southwest and west, respectively. The emirate covers an area of approximately 1,684 square kms, characterized by a diverse landscape of rugged mountains, desert plains, and coastal areas (Figure 1). The population of Ras al Khaimah has been steadily growing in recent years, primarily due to economic development and immigration (Figure 2) The emirate is estimated to have a population exceeding 400,000 people, with a diverse demographic makeup consisting of Emiratis and expatriate communities from various countries. The city of Ras al Khaimah serves as the capital and largest urban center, hosting a significant portion of the population.

Ras al Khaimah experiences an arid climate, characterized by hot summers and mild winters. Summer temperatures often exceed 40°C (104°F) and can reach as high as 50°C (122°F) in the peak months of July and August. Winters are relatively cooler, with temperatures averaging around 15-25°C (59-77°F). Rainfall is very less throughout the year, occurring mainly during the winter months, with an average annual precipitation of less than 150 mm. The study area is primarily influenced by sedimentary rocks, formed over millions of years.

The present study area is situated between Longitudes 55o50’ & 56o20’ latitudes 25o20’ & 26o10’ total area comprises of 1830 Sq. Km (Figure 1) and identified 9 basins. Study area is bounded with mountains on eastern side and there are several Wadis namely Wadi Al Beeh, Wadi Shehah, Wadi Haqeel, Wadi Sal which contribute large amounts of surface runoff from their mountain watersheds to the Ras Al Khaimah region during severe storms. Some evidences of recent floods happened along this region is shown as field images in Figure 3.

2.2 Materials and Methods

This study employed various vector and raster data to study the flash flood susceptibility of the study area. The major data employed in this study is the Digital Elevation Data (DEM) extracted from Shuttle Radar Topography Mission (SRTM) data with 30m resolution. Further, with DEM as base data various topographic and morphometric parameters required for the study

has also been derived. Morphometric parameters were selected based on their influence on drainage characteristics, runoff generation, terrain configuration, and water accumulation. The parameters were integrated into the susceptibility assessment using their respective weights or ranks to represent their relative contributions to flood susceptibility. Along these datasets, as this study focus on flood susceptibility, rainfall is also considered as a major requirement, which is downloaded from the CHRS RainSphere portal (https://rainsphere.eng.uci.edu). The materials used in the study are listed below in Table 1.

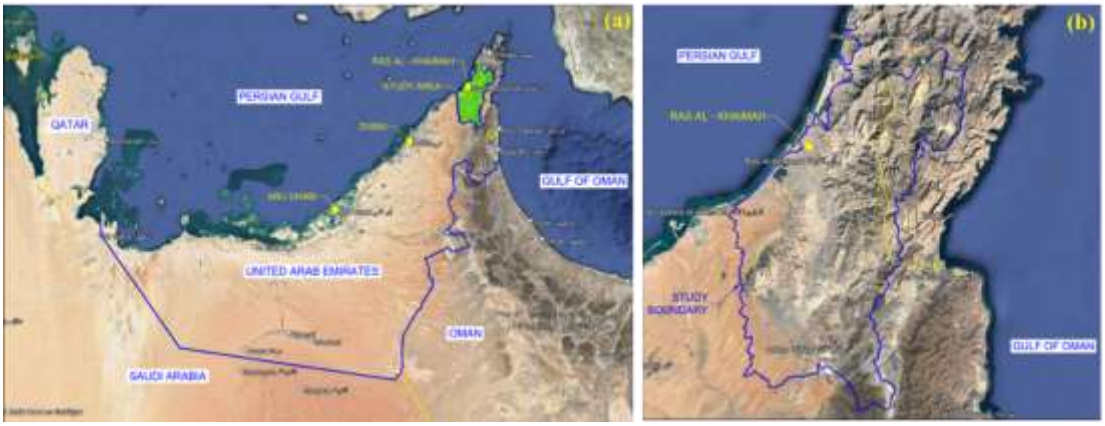

Figure 1. Maps showing the location of study area (a) UAE and (b) Ras al Khaimah

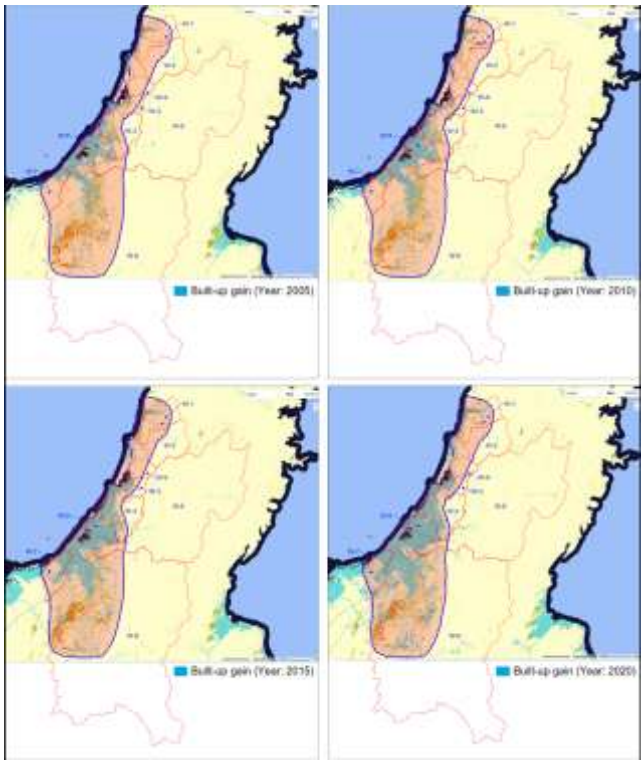

Figure 2. Maps showing the urbanization trend from 2000 to 2020

Table 1. List of datasets used in this study

S.No	Maps	Data Source
1	DEM	SRTM, USGS Earth Explorer, 30m resolution
2	Rainfall	CHRS rainsphere (2001 - 2022)

3	Temporal Urban sprawling map	Google Earth Multidate imagery
4	Elevation	Derived from DEM
5	Slope	Derived from DEM



Figure 3. Recent floods in Ras Al Khaimah (Source: National Newspapers)

This study was performed using a GIS-based framework implemented in the ArcGIS 10.8 software which helps in integrating and analyzing the spatial datasets doe flood susceptibility assessment. The DEM data is used as the primary input for terrain analysis, enabling the extraction of elevation, slope and flow characteristics. Following this, the hydrology toolset in ArcGIS is used to derive the hydrological parameters such as catchment delineation, flow direction, flow accumulation, etc. A total of 13 parameters were determined and analysed for this study. All the derived layers were further processed to identify the flood susceptibility. All spatial layers were standardized and integrated within the GIS environment to support subsequent multi-criteria analysis and identification of flood-prone zones (Figure 4).

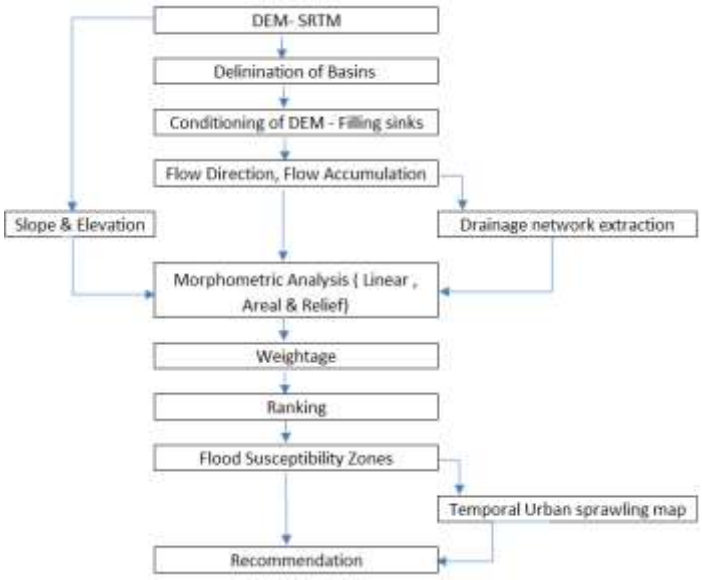

Figure 4. Flowchart depicting the methodology adopted in this study

2.2.1. Linear Aspects

The streams and its network are typically named as linear aspects and these are classified as one-dimensional property. Basin perimeter (P), Basin length (Lb), Stream order (U), Stream length (Lu) and Total number of streams (Nu) are the main characteristics under the linear aspect.

2.2.2. Areal Aspects

Areal aspects are two-dimensional features which includes, Basin area (A), Drainage density (Dd), Length of overland flow (Lo) and Stream frequency (Fs). These are defined by few parameters such as Elongation ratio (Re), Circularity ratio (Rc)and Shape factor (Sf).

2.2.3. Relief Aspects

The elevation difference between outlet points and start point in watershed are taken as the relief aspect. These are three-dimensional properties. The Basin relief (H), Relief ratio (Rr), Relative relief ratio (Rv), Basin slope (Bs), Ruggedness number (Rn) and Hypsometric integral (HI) are important characteristics of a watershed.

The final susceptibility index was classified into five categories: very low, low, moderate, high, and very high. The classification was based on the distribution of index values using the adopted classification method.

3. RESULTS AND DISCUSSION

3.1 Morphometric Analysis

Morphometric analysis provides a quantitative framework for evaluating the physical and hydrological characteristics of a drainage basin, which are critical in understanding flood susceptibility. It involves the measurement and analysis of terrain attributes, drainage network geometry and basin configuration, all of which influence runoff generation, flow velocity and water accumulation patterns. Parameters such as drainage density, stream frequency, bifurcation ratio, basin shape, elongation ratio and relief characteristics are widely used to interpret the hydrological behaviour of a watershed (Horton, 1945; Strahler, 1964).

The results of the present analysis indicate that morphometric parameters play a decisive role in controlling flood response. For instance, higher drainage density and stream frequency suggest a well-developed drainage network, which facilitates rapid surface runoff and reduces infiltration capacity, thereby increasing flood susceptibility. Similarly, basins with high elevation (Figure 5a) and steep slope (Figure 5b) tend to increase the water flow which results in high discharge and flow especially in the short rainfall duration (Schumm, 1956). As morphometric analysis is one of the important parameters in determining the flood susceptibility, morphometric analysis serves as a fundamental component which provides a scientific basis for flood risk assessment, watershed management and sustainable land-use planning (Nag, 1998).

3.2 Linear Parameters

3.2.1. Basin Length (LB)

The basin length is calculated following the methodology and suggestions made by Schumm (1956). In the present study, nine (9) sub-basins were delineated (Table 2), with considerable variation in basin lengths, in which, W-8 shows the longest basin length (81.66 km) and W-3 has the shortest (4.72 km). These kind of observed variation in basin length throughout the study area implies the hydrological response of the basin. Larger basins will have longer flow paths and increased time of concentration and in other case, the smaller basins will be associated with shorter response times and quicker runoff concentration, which makes them more susceptible to rapid flooding. Thus, basin length is an important parameter influencing runoff dynamics and flood susceptibility within the basin.

3.2.2. Stream order (Su)

Strahler has proposed the stream ordering technique in his study during 1952. The concept is quite easier, when two streams of same order converge, there is an increment to the next higher order. Based on this classification, the study area shows a maximum order of the 5th (Figure 5 c &d). These presence of higher-order streams indicates a well-developed and hierarchically organized drainage system, suggesting efficient runoff collection and channel integration.

3.2.3. Stream Length (Nu)

The summation of individual stream lengths of each order provides the stream length of that order. The stream length is a measure of the hydrological characteristics of the bedrock and the drainage extent. Wherever the bedrock and formation are permeable, only a small number of relatively longer streams are formed in a well-drained watershed, a large number of streams of smaller length are developed where the bedrocks and formations are less permeable (Sethupathi et al., 2011). Basin W-8 has the highest weightage and W-3, W-5, W-9 has the lowest weightage (Figure 6a).

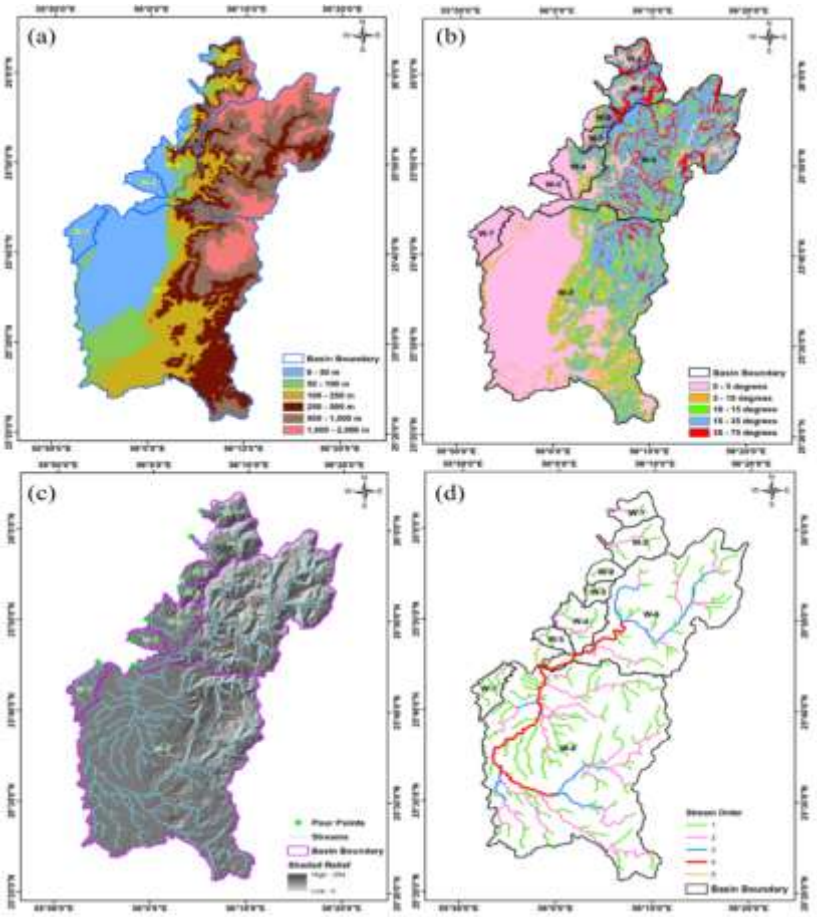

Figure 5. Maps showing the (a) Digital Elevation Model (b) Slope (c) Shaded Relief and (d) Stream Order of the study area

3.2.4. Bifurcation ratio (Rb)

According to Schumm, 1956, the bifurcation ratio (Rb) is the ratio of the number of the stream segments of given order (Nu) to the number of segments of the next higher orders (Nu+1). It is a dimensionless property and shows the degree of integration prevailing between streams of various orders in a drainage basin. Under the study the bifurcation ratio varies from 6.67 to 1.33. Basin W-6 has the highest bifurcation ratio of 6.67 and basins W-1 & W-2 are the lowest bifurcation ratio. Generally, higher the ratio higher the runoff generation, which is generalized as mountainous and lower values depicts the ground form as rolling and flat basins. Basin W-6 has the highest weightage and W-1, W-2, W-3, & W-7 has the lowest weightages (Figure 6b).

Table 2. Details of Linear Parameters

Basin No	Basin Length (Lb) in Km	Basin Perimeter (P) in Km	Stream Number (Nu)	Stream Length (Lu)	Bifurcation Ratio (Rb)
W-1	8.33	35.72	7	11.43	1.33
W-2	15.05	55.35	7	24.54	1.33

W-3	4.72	24.58	5	7.10	1..50
W-4	15.33	55.70	13	29.40	6.40
W-5	5.84	32.02	3	7.18	2.00
W-6	61.2	177.01	95	206.26	6.67
W-7	13.34	47.92	5	24.56	1.50
W-8	81.66	246.85	190	568.38	5.81
W-9	4.89	22.50	3	5.38	2.00

3.3 Areal Parameters

The detailed values obtained during the analysis of the data for areal parameters are provided in Table 3.

3.3.1. Basin Area (A)

In the present study, significant variation in basin area was observed among the delineated sub-basins. Basin W-8 represents the largest drainage area (1055.57 km²), while basin W-3 is the smallest (17.92 km²). The remaining basins exhibit intermediate values, ranging from 495.03 km² to 22.72 km². The variation in basin area has a direct influence on runoff generation, as larger basins tend to contribute higher volumes of runoff due to their greater catchment extent. Accordingly, basin W-8 is assigned a higher weightage in flood susceptibility assessment, whereas basin W-3 is considered less significant in terms of runoff contribution.

3.3.2. Basin Perimeter (P)

The basin perimeter represents the total length of the outer boundary that separates one watershed from adjacent catchments, typically defined by ridge lines. In the present study, basin W-8 exhibits the longest perimeter (246.85 km), whereas basin W-9 has the shortest perimeter (22.5 km). Variations in basin perimeter reflect differences in basin size and shape complexity. Therefore, basin W-8 is likely to have a greater contribution to runoff generation compared to smaller basins such as W-9, which have more limited spatial extent.

3.3.3. Elongation ratio (Re)

According to Schumm, 1956, the elongation ratio (Re) is the ratio of diameter of a circle of the same area of the basin to the maximum basin length typically, values range between 0 to 1 (Figure 6f). Value 0 represents the elongated shape and 1 represents the circular shape. Higher the values of elongation ratio represent the higher infiltration capability and low runoff, whereas lower the values of elongation ratio represents the lower infiltration capability and higher the chances of erosion and higher peak flow.

3.3.4. Form Factor(f)

It is a mathematical factor derived from the ratio of the basin area and the square of basin's length. Form Factor represents the shape of the basin. It gives the prediction to runoff. In the study, W-9 has the highest form factor and W-6 has the lowest factor. Higher the value depicts the high level of discharge in a short duration rainfall event. The basins W-3 and 9 has higher weightage and W-6 lower (Figure 6e).

3.3.5. Drainage Density (Dd)

It is a measure of the total stream length in an identified basin to the total area of the basin (Strahler, 1964). In the current study, drainage density varies from 0.63 to 0.24. The basin W-7 has the highest value of 0.63 and basin W-9 has the lowest value of 0.24. Higher drainage density indicates a well-developed channel network, reduced infiltration, and enhanced surface runoff, thereby increasing flood susceptibility. Accordingly, basin W-7 is likely to generate higher runoff, while basin W-9, with lower drainage density, may exhibit comparatively reduced runoff. Based on this, basins W-7 and W-8 are assigned higher weightage, whereas basin W-9 is given lower weightage in the flood susceptibility assessment (Figure 6h).

3.3.6. Stream Frequency (Fs)

It is defined as the ratio of the total number of stream segments of all order in a basin to the basin area (Horton, 1945). In the present study, the stream frequency parameter highest value identified in basin W-3 and lowest in basin W-2. Higher the value of ratio, higher the potential for high runoff. Here basin W-3 has higher top and Basin W-1 lower (Figure 6d).

3.3.7. Infiltration Number (If)

The infiltration number identifies the characteristics of basin's infiltration (Faniran, 1968). It is the relationship between the frequency of the basin and drainage density. Highest infiltration number observed in basin W-3 as 0.70and lowest in W-7 as 0.20. Higher the infiltration number represents the higher runoff. Accordingly, basin W-7 weighted higher and W-3 provided with lower weightage (Figure 6g).

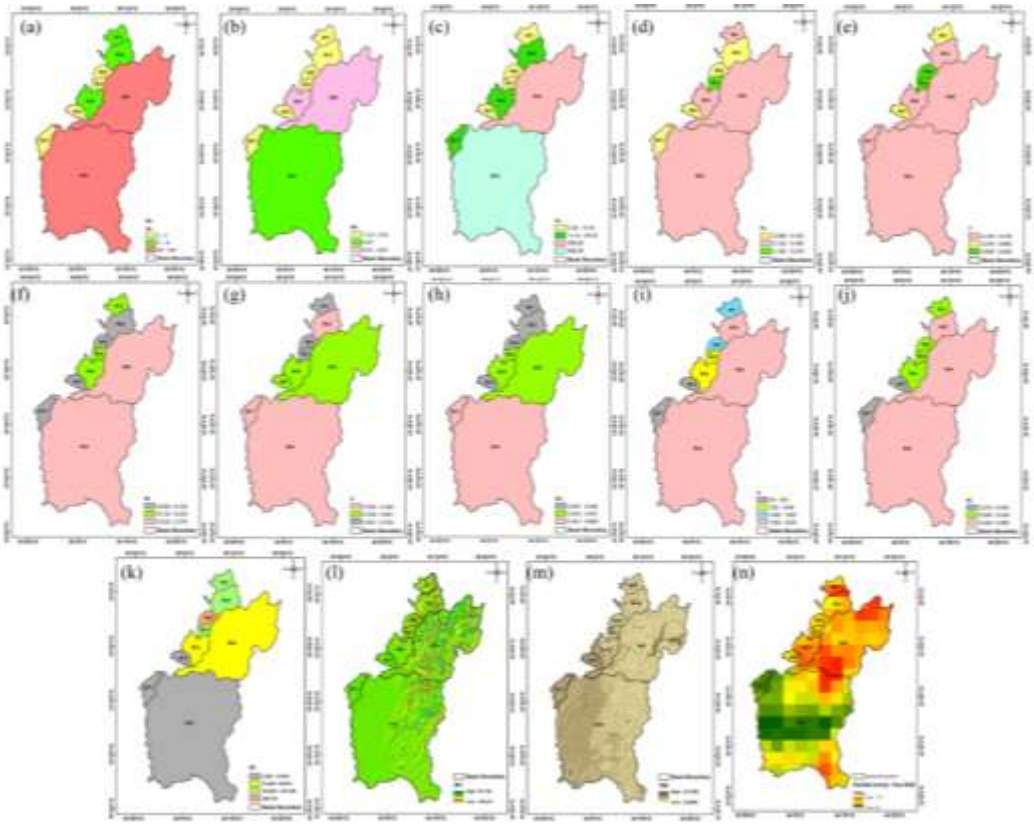

Figure 6. Maps showing (a&b) Linear, (c-h) Areal and (i-k) Relief parameters of the study area

3.4 Relief Parameters

The detailed values obtained during the analysis of the data for relief parameters are provided in Table 4.

3.4.1. Basin Relief (H)

The Basin Relief parameter visualize the elevation difference between the lowest and highest elevations within the given basin. The results indicate maximum difference in basin W-6 with 2059m of level difference and minimum elevation noticed in W-5 which is 60m. In the study, the predominantly the basin elevation difference are above 500m. It can be visualized that, the higher the level difference the probability of flash flood is higher. In the perspective, basins W-1,2,3,4,6,8,9 has higher potential for flash flood events. Basin W-6 ranks highest and W-5, W-7 ranks lowest (Figure 6i).

3.4.2. Relief Ratio (Rr)

Schumm (1946) states that the maximum relief to horizontal distance along the longest dimension of the basin parallel to the principal drainage line is termed as relief ratio. Difference in the elevation between the highest point of a basin and the lowest

point on the valley floor is termed as the total relief of that river basin. In the present study the ratio varies from 5.40 to 305.78. The highest value observed in W-9 and lowest value in W-7. The ratio increases with the decreasing drainage area and size of a given drainage basin (Gottschalk, 1964). Higher the relief ratio parameters project the low lag times and sudden peak flows. This will lead to flash floods conditions. Basin W-9 ranks highest and W-5, W-7 ranks lowest (Figure 6k).

Table 3. Details of Areal Parameters

Basin No	Basin Area (Km2)	Stream Frequency (Fs)	Form FACTOR (f)	Texture Ratio (Rt)	Drainage Density (Dd)	Infiltration Number (If)	Basin perimeter (P) in Km	Elongation Ratio (Re)
W-1	35.90	0.20	0.52	0.20	0.32	0.61	35.72	0.81
W-2	71.57	0.10	0.32	0.13	0.34	0.29	55.35	0.63
W-3	17.92	0.28	0.80	0.20	0.40	0.70	24.58	1.01
W-4	66.69	0.19	0.28	0.23	0.44	0.44	55.70	0.60
W-5	23.61	0.13	0.69	0.09	0.30	0.42	32.02	0.94
W-6	495.03	0.19	0.13	0.54	0.42	0.46	177.01	0.41
W-7	39.11	0.13	0.22	0.10	0.63	0.20	47.92	0.53
W-8	1055.57	0.18	0.16	0.77	0.54	0.33	246.85	0.45
W-9	22.72	0.13	0.95	0.13	0.24	0.56	22.50	1.10

3.4.3. Ruggedness Number (Rn)

It defines the slope steepness and length. Strahler,1964 describes ruggedness number (Rn) as the product of maximum basin relief and drainage density and it usually combines slope steepness with its length. Higher the ruggedness number probability of flash flood. From the study, basin W-8 has the highest ratio with 0.86 and W-7 is the lowest with 0.05. Basin W-6, W-8 ranks highest and W-5, W-7 ranks lowest. (Figure 6j).

Table 4. Details of Relief Parameters

Basin No	Basin Relief (H) in m	Ruggedness Number (Rn)	Relief Ratio (Rr)
W-1	1411	0.45	169.33
W-2	1897	0.64	124.82
W-3	951	0.38	201.39
W-4	719	0.32	46.92
W-5	60	0.02	10.28
W-6	2059	0.86	33.65
W-7	72	0.05	5.40
W-8	1594	0.86	19.52
W-9	1495	0.35	305.78

3.5. Prioritization of basin for flood susceptibility

As discussed, this present study utilized thirteen morphometric parameters such as basin relief, relief ratio, ruggedness number, basin area, stream frequency, drainage density, form factor, texture ratio, bifurcation ratio, stream length, stream number and basin length. Each parameter was assigned a weightage based on its relative influence on runoff generation and flood potential,

and individual basins were ranked accordingly. The cumulative scores derived from all parameters were then used to obtain the overall ranking of each basin (Table 5). The integrated analysis provides a comprehensive assessment of spatial variability in flood susceptibility within the study area. With the recent urbanisation included the final flood susceptibility map is presented in Figure 7.

Table 5. Weightage and Ranks assigned for each parameter for Flood susceptibility mapping

Basin Number	Stream Number	Stream Length	Bifurcation Ratio	Texture Ratio	Basin Area	Stream frequency	Form Factor	Drainage Density	Infiltration Number	Relief Ratio	Basin Relief	Ruggdness Number	Basin Slope	Total Ranking
W-1	2	2	2	3	2	4	3	3	1	3	3	3	5	36
W-2	2	3	2	2	3	1	3	3	5	3	5	4	5	41
W-3	1	1	2	3	1	5	5	4	1	4	2	3	3	35
W-4	3	3	5	3	3	3	3	4	3	2	2	3	2	39
W-5	1	1	3	1	2	2	4	3	3	1	1	1	1	24
W-6	4	4	5	5	4	3	1	4	3	2	5	5	5	50
W-7	1	3	2	2	2	2	2	5	5	1	1	1	1	28
W-8	5	5	4	5	5	3	2	5	4	2	4	5	4	53
W-9	1	1	3	2	2	2	5	2	2	5	4	3	3	35

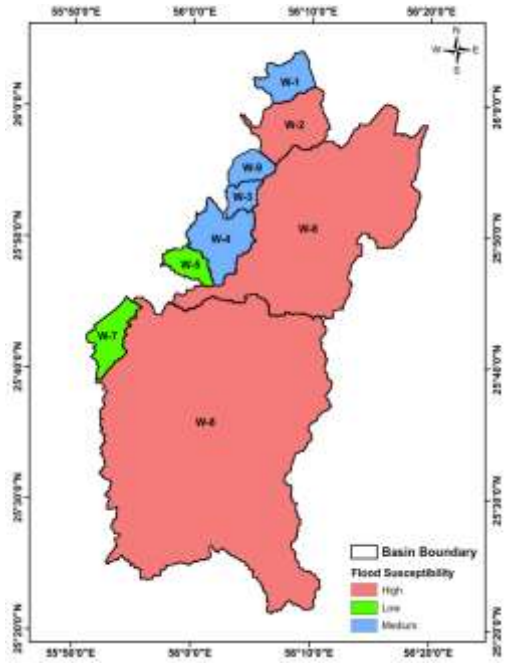

Figure 7. Flood Susceptibility map of the study area

4. CONCLUSION & RECOMMENDATIONS

This study assesses flood susceptibility across nine drainage basins contributing to flooding in the Ras Al Khaimah region using morphometric analysis. The results indicate that basins W-2, W-6 and W-8 fall under very high susceptibility, while W-1, W-3, W-4 and W-9 show moderate susceptibility and W-5 and W-7 are showing low susceptibility. These variations highlight the role

of basin characteristics in controlling runoff behaviour and flood potential. Further, urban expansion between 2005 and 2020 shows significant growth in basins W-8, W-3, W-4 and W-9, increasing the exposure to flood risk. In particular, basin W-8 requires immediate attention due to the overlap of high susceptibility and rapid urbanization. That can be made through implementing various measures such as early warning systems, floodplain zoning, land-use regulations, infrastructure improvements and nature-based solutions to enhance resilience and mitigate the impacts of flooding.

To reduce the flash flood impacts it is recommended to study various sustainable Water resources management approaches such as Managed Aquifer Recharge (MAR), sponge city concepts and Pumped Head Storage (PHS) application may help by storing more water from wet periods for use during droughts and power storage. The assessment primarily considers terrain and morphometric characteristics and does not fully account for dynamic factors such as rainfall intensity, soil infiltration, land-use changes, and river discharge. Therefore, the resulting map represents relative flood susceptibility rather than actual flood-hazard prediction. Detailed hydrological and hydraulic modelling is required for comprehensive flood-hazard assessment.

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AUTHOR CONTRIBUTIONS

Sreepathy Rangarajan: Conceptualization, Data Curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Jegankumar R: Supervision, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

All data used in the generation of this manuscript are included within the manuscript.

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