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Morphometric Characterization and Dual Analysis for Flash Flood Hazard Assessment of Wadi Al-Lith Watershed, Saudi Arabia

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Abstract: Flash floods are one of the most hazardous natural events globally, characterized by their rapid onset and unpredictability, often overwhelming emergency preparedness and response systems. In the arid environment of Saudi Arabia, Wadi Al-Lith watershed is particularly prone to flash floods, exacerbated by sudden storms and the region's distinct topographical features. This study focuses on the morphometric characterization and comparative analysis of flash flood risk within the Wadi Al-Lith basin. To assess flood susceptibility, two widely adopted methodologies were employed: the morphometric ranking approach and El-Shamy's method. A 12.5-m resolution ALOS PALSAR digital elevation model (DEM) was used to delineate the watershed and generate a detailed drainage network via Arc-Hydro tools in the ArcGIS 10.4 software. Fifteen morphometric parameters were analyzed to determine their influence on flood potential and hazard prioritization. The findings of this study provide crucial insights for regional flood risk management, offering an improved understanding of flash flood dynamics and assisting in developing effective mitigation strategies for Wadi Al-Lith and similar environments. The findings reveal that Wadi Al-Lith comprises multiple sub-catchments with varying degrees of vulnerability to flash flooding. According to the morphometric hazard analysis (MHA), certain sub-catchments, including sc-2, sc-4, sc-5, sc-6, sc-10, sc-12, sc-13, and sc-15, emerge as highly susceptible to flood hazards, while others (sc-1 and sc-9) fall into moderate risk categories. In contrast, the application of El-Shamy's method provides a different ranking of flood risks across the watershed's sub-catchments, offering a comparative view of flood susceptibility. The insights gained from this dual-analysis approach are expected to support the development of targeted flood prevention and mitigation strategies, which are essential for minimizing the future impacts of flash flooding in the Wadi Al-Lith watershed and ensuring better preparedness for local communities.

Keywords: flash flood hazard assessment; morphometric parameters; dual analysis; geospatial analysis; Wadi Al-Lith watershed; Saudi Arabia

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1. Introduction

Flash floods are among the most destructive hydrological hazards worldwide, characterized by their rapid onset, short duration, and immense destructive capacity. These floods can occur within minutes or hours after intense rainfall, often resulting in catastrophic consequences for affected areas. The unpredictability of flash floods, coupled with their ability to inflict widespread damage, makes them particularly dangerous. They pose significant threats to human life, property, infrastructure, and overall economic development, particularly in regions with limited flood preparedness and response mechanisms [1–5]. The severity of flash floods is primarily influenced by the intensity and duration of precipitation events; however, several other hydrological and geomorphological factors play crucial roles in determining flood behavior and impact [6,7]. These include evaporation rates, soil infiltration capacity, lithology, drainage network configuration, land cover, and both natural and human-induced alterations to the environment [5,8]. Watersheds, as the primary geomorphic units in hydrological systems, provide an essential framework for understanding and managing extreme hydrological events like flash floods. A watershed is defined as an area of land where all surface water converges to a single point, typically at the outlet of a river system. The characteristics of a watershed, such as its size, shape, slope, and drainage network, govern its hydrological response to rainfall, making watershed-scale analysis vital for flood risk assessments. Morphometric analysis, which involves the quantitative evaluation of the physical properties of a watershed, has proven to be an effective tool for understanding and predicting hydrological processes. By examining key morphometric parameters such as stream order, stream length, drainage density, stream frequency, basin area, perimeter, and shape factor, researchers can infer how different watersheds will respond to rainfall events and how susceptible they may be to flash flooding [2,8,9]. The foundation of morphometric studies can be traced back to the pioneering work of Refs. [10,11], which developed systematic approaches to classifying and quantifying watershed and stream network characteristics [12]. These early studies laid the groundwork for modern hydrological research, where morphometric analysis plays a pivotal role in flood risk modeling, erosion control, groundwater assessment, and watershed management. The ability to predict flash flood potential based on watershed morphology has made this approach particularly useful in areas where extreme weather events are becoming more frequent and severe due to climate change and other environmental factors [13,14]. Flash flood risk is strongly influenced by the drainage network and geomorphological features of a watershed. The geometry of the drainage network, including stream density, drainage pattern, and stream frequency, is controlled by the underlying geology, topography, and climatic conditions [15]. Variations in these factors can lead to significant differences in flood susceptibility between watersheds. For example, a watershed with a high drainage density and steep slopes is likely to experience faster runoff and higher flood peaks compared to a flatter watershed with a lower drainage density. This makes the detailed morphometric characterization of watersheds essential for identifying areas most at risk of flash flooding.

Historically, the delineation and analysis of drainage networks required labor-intensive methods, such as field surveys, topographic map analysis, and aerial photography. While effective, these methods were time consuming and often lacked the precision needed for large-scale studies. The advent of remote sensing (RS) and geographic information systems (GIS) has revolutionized watershed analysis by providing tools for rapid, accurate, and large-scale assessment. Remote sensing, using satellite imagery and digital elevation models (DEMs), allows for the precise delineation of watershed boundaries and the extraction of morphometric parameters. GIS tools, such as Arc-Hydro, offer the ability to automate the processing of spatial data, enabling researchers to quickly and accurately evaluate watershed characteristics and flood susceptibility [16–19]. The application of remote sensing and GIS technologies is particularly relevant in arid and semi-arid regions like Saudi Arabia, where flash floods pose a recurring threat due to the combination of sporadic, intense rainfall events and steep, rugged terrain. Wadi Al-Lith, located on the western coast of Saudi Arabia, is an area that experiences frequent flash flooding during the rainy season [20]. This region, characterized by ephemeral streams and a highly variable climate, presents significant challenges for flood risk management. Given its susceptibility to extreme weather events, there is a critical need to understand the morphometric properties of the Wadi Al-Lith watershed to assess its flood potential and to inform effective flood mitigation strategies.

In this study, we conduct a comprehensive morphometric analysis of the Wadi Al-Lith watershed using high-resolution DEMs and GIS-based tools. Our goal is to assess the flash flood susceptibility of the region by analyzing key morphometric parameters and comparing the results of two prominent flood risk modeling approaches: the morphometric ranking approach and El-Shamy's method. While both methods rely on morphometric parameters to assess flood risk at the sub-basin level, they offer distinct perspectives on the prioritization of flood-prone areas and have not been extensively compared in previous studies. This research aims to provide a comparative analysis of these methods to determine their relative effectiveness in predicting flood susceptibility in arid regions. The specific objectives of this study are (1) to perform a detailed morphometric characterization of the Wadi Al-Lith watershed using remote sensing and GIS techniques; (2) to assess the flash flood susceptibility of the watershed using the morphometric ranking approach (MRA) and El-Shamy's method; (3) to compare and evaluate the accuracy and reliability of these two flood risk modeling approaches for identifying flood-prone areas; and (4) to provide recommendations for improved watershed management and flash flood mitigation based on the results of the comparative analysis. The findings of this study will not only contribute to the scientific understanding of flash flood dynamics in Wadi Al-Lith but will also provide practical tools and insights for managing flood risk in other similarly vulnerable arid regions. By integrating advanced geospatial techniques with established morphometric methodologies, this research offers a robust framework for flood risk assessment and disaster preparedness in Saudi Arabia.

2. Study Area

The Wadi Al-Lith watershed, located in western Saudi Arabia, is bordered by the As-Sarawat Mountains to the east and north and by the Red Sea to the west. Spanning an area of approximately 3089 km^2, the basin extends for 109 km (Figure 1). It is lies between latitudes 20°00′ and 21°15′ E and longitudes 40°10′ and 40°50′ N. Al-Laith City is located downstream and is accessible by main roads 180 km southwest of Mecca City. With maximum evaporation rates in July (200 mm) and little winter precipitation from November to March, the area experiences an arid to semi-arid environment. September has the maximum speeds (39 km/h) according to seasonal wind records.

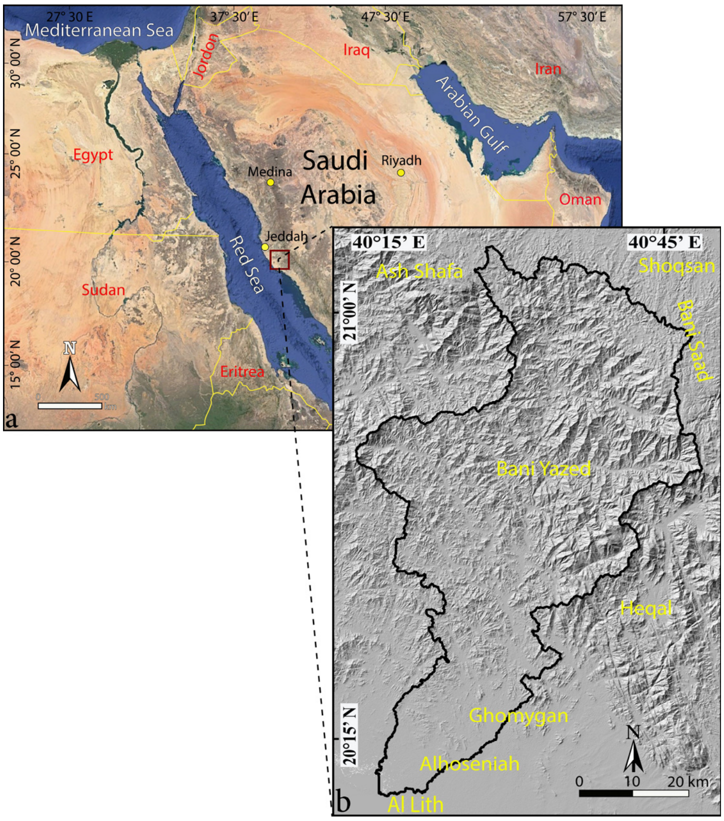

Figure 1. (**a**) Regional map of Saudi Arabia and (**b**) hillshade map showing location of the Wadi Al-Lith watershed.

The Wadi Al-Lith watershed, which has a total area of 3262 km^2 and lies 200 km south of Jeddah City, provides a varied geology, including Quaternary alluvial and eolian deposits in the lowlands, Tertiary volcanics, and Proterozoic rock units. Obvious damage has been inflicted by semi-annual flood events, especially in 2009 and 2010, as water is controlled onto lowland deposits by rough upstream reliefs. Different geomorphological zones and the interplay between the mountainous relief and the coastal plain zone have provided the diverse geomorphology of the Wadi Al-Lith watershed. It ranges from the Red Sea's sea level to the mountains' 2657 m elevation. The three different zones of the watershed's geomorphic characteristics are produced by these elevation differences, which also impact water flow. Because of its steep slopes, rocky ridges, and major rivers and streams, the mountainous upstream zone (500–2657 m) has a higher risk level of flash floods based on its quick surface runoff during rainstorm events. In addition, landslides, silt transfer downstream, and soil erosion processes happen in this area (Figure 2).

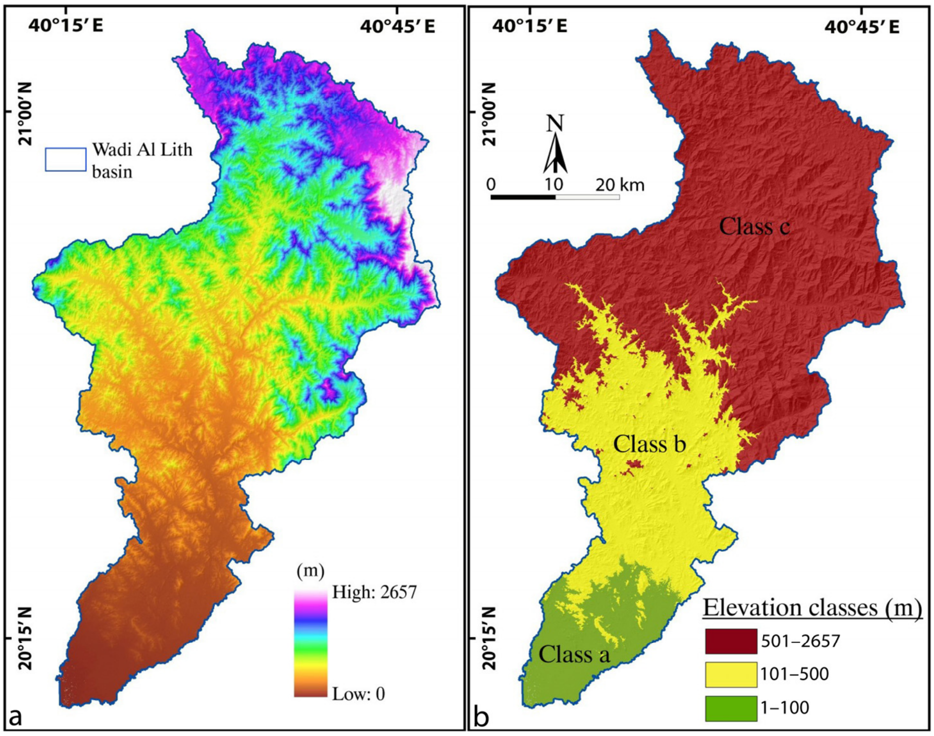

Figure 2. (**a**) A digital elevation model map and (**b**) the geomorphological zones of the Wadi Al-Lith watershed.

Deep valleys and moderate slopes define the midstream transitional zone (100–500 m) (Figure 2), which guides water flow and sediment transport from the highlands to the coastal plain zone. Rivers and channels enlarge, and material starts to accumulate here, controlling flow in the direction of the coastal zone. Because of its low elevation and poor drainage patterns, the coastal plain zone (at sea level to 100 m) contains flat alluvial deposits that are sustainable to flash flooding events. Water quickly builds up during rainstorms, and the Red Sea's tidal influences can exacerbate flash flood situations.

Wadi Al-Lith's geomorphology is affected by its arid to semi-arid conditions, which provides high temperatures and evaporation in the summer and little rainfall, mostly in the winter season. Throughout the basin, soil erosion and sediment deposition are also influenced by seasonal wind systems. The region's climate conditions and relief combine to make it especially susceptible to flash floods; the low-lying coastal plain, incised transitional zone, and steep slopes all contribute to a dynamic system of water and sediment transport. These factors have contributed to extreme flash flood events, highlighting the necessity of efficient flash flood control estimates.

3. Materials and Methods

For the morphometric characterization and flash flood hazard assessment of the Wadi Al-Lith watershed, this study incorporated a range of high-resolution geospatial datasets and specialized analytical techniques. At the core of the analysis, the Advanced Land Observing Satellite (ALOS) phased array type L-band synthetic aperture radar (PALSAR) digital elevation model (DEM) was utilized. The DEM, with a 12.5 m spatial resolution, was selected for its high accuracy and suitability for hydrological and morphometric studies. These data were acquired from the https://search.asf.alaska.edu/website (accessed on 27 February 2024) through the ASF Data Search Vertex, with the final dataset accessed on 15 May 2023. To cover the entirety of the Wadi Al-Lith basin, six separate ALOS PALSAR scenes were gathered, which were subsequently mosaicked into a seamless elevation model. This process ensured the generation of a unified topographical representation of the study area. In addition to the DEM, topographic maps of the basin, scaled at 1:50,000, were digitized and integrated into the analysis. The combination of DEM and topographic data allowed for the extraction of essential basin characteristics, providing a comprehensive dataset for detailed morphometric and hydrological assessments. In the current study, data processing was carried out using both QGIS 3.16 and ArcGIS 10.4. Spatial analysis and hydrological processing, including catchment delineation, flow direction, and flow accumulation, were performed using ArcGIS 10.4. Preprocessing of data, format conversions, and data visualizations were prepared by QGIS 3.16. When used in tandem, both software guaranteed accuracy and adaptability throughout the many stages of processing. Gaps within the DEM were filled using interpolation techniques to ensure a smooth elevation surface without missing values. Furthermore, hydrological tools available in these geospatial platforms, such as flow direction, flow accumulation, pour point snapping, and stream order algorithms, were applied to delineate drainage networks, sub-basin boundaries, and the overall watershed structure. The accuracy of the delineated drainage systems was cross verified by comparing them with manually digitized drainage systems from the topographic maps.

A critical part of the methodology involves improving the DEM accuracy for hydrological modeling, particularly for stream network extraction. To this end, a sink elimination process was applied to remove any local depressions (sinks) within the DEM that could disrupt the natural flow of water. Sinks are areas where water would appear to collect due to erroneous elevation values, preventing accurate flow direction modeling. The Arc-Hydro toolset, developed by the University of Texas, was used for this purpose. It allowed for seamless manipulation of the DEM to eliminate sinks and ensure that flow was accurately simulated across the landscape. By employing the D8 flow direction algorithm, the Arc-Hydro toolset assigned flow direction to each cell, ensuring that water followed the steepest downslope path. A flow accumulation grid was then derived, highlighting the areas of greatest water convergence and enabling the identification of stream networks. To determine the stream network, a threshold area of 1% flow accumulation was applied, ensuring that only significant streams were included in the network. Once the stream network was extracted, it was classified according to the Strahler stream ordering system, a widely used method in morphometric studies. In this system, the smallest unbranched tributaries are designated as first-order streams, and when two first-order streams converge, they form a second-order stream, and so on. The number of streams at each order was recorded, and the length of each stream was calculated. Additionally, the watershed boundaries were delineated using the D8-based flow direction grid, and the precision of these boundaries was compared against manually digitized boundaries derived from Survey of Saudi Arabia topographical sheets at a 1:50,000 scale, ensuring a high degree of spatial accuracy. The full processing steps are explained in Figure 3.

To give a more thorough, accurate, and significant assessment of flash flood risk in the Wadi Al-Lith watershed, this study used two different effective methods: the morphometric ranking technique and El-Shamy's approach. The morphometric ranking approach makes it possible to characterize the watershed according to important geomorphological elements that are essential for understanding flood risk including slope and drainage density. El-Shamy's approach, however, better measures and predicts flood vulnerability by integrating these morphometric variables with hydrological data. Integrating the analysis of both approaches required the usage of both: El-Shamy's method provided a comprehensive view by combining hydrology and geomorphology, while the morphometric ranking approach provided a more in-depth, factor-based analysis. These two very indicative approaches were selected because they improve the dependability of the flood hazard assessment in the context of the Wadi Al-Lith watershed and complement one another, even if any other techniques were taken into consideration.

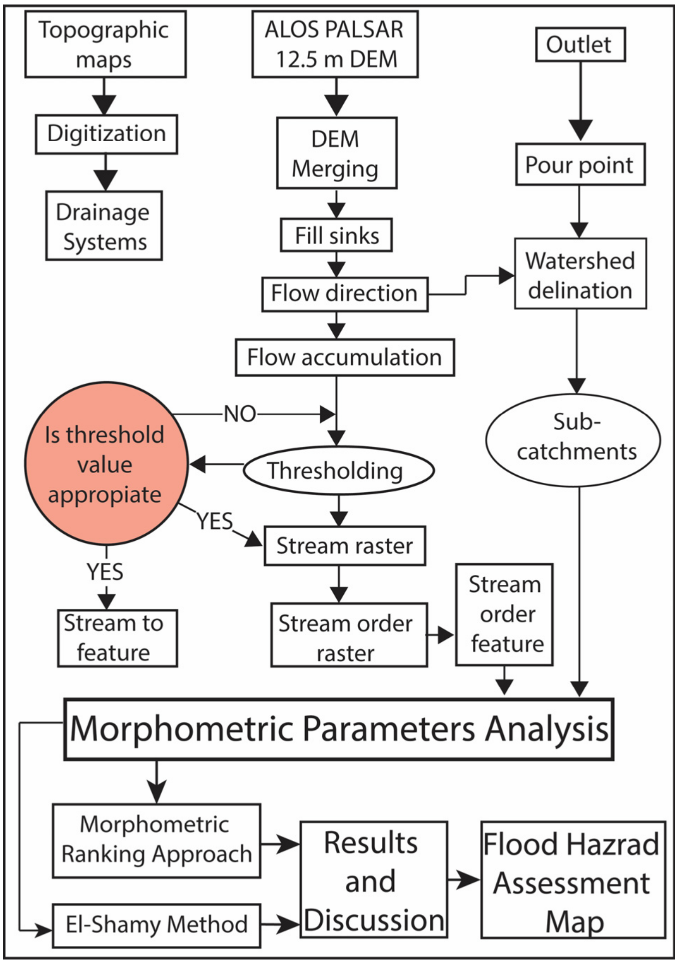

Figure 3. Chart illustrating the drainage systems and morphometric parameters analysis of the Wadi Al-Lith watershed.

The extraction of the drainage network and watershed boundaries from the DEM was followed by the computation of various morphometric parameters. Based on their influence on flash flood risk, these morphometric parameters were divided into two categories. The first group consisted of parameters that are directly related to flood risk, meaning that higher values indicate a greater likelihood of flash flooding. These parameters included total basin area (A), drainage density (Dd), stream frequency (Fs), total number of streams (Ns), stream order (Os), total stream length (Ls), and circulatory ratio (Rc) (see Table 1) [15]. The second group contained two parameters that have an inverse relationship with flood risk, where higher values correspond to lower flash flood susceptibility. These were the elongation ratio (Re) and shape factor (Sh-f) (see Table 1). In the present study, the Wadi Al-Lith watershed is classified into 15 sub-catchments utilizing orders ≥ 3 (Figure 4a,b).

Table 1. The most effective morphometric parameters applied in the present study and their equations.

Title 1	Title 3	References
Basin length (Lb)	Distance between outlet and farthest point on basin boundary	[10]
Basin width (Wb)	Wb = A/Lb	[21]
Length width ratio (Rlw)	L/W	[10]
Stream orders (Os)	Hierarchical order	[11]
Stream numbers (Ns)	Ns = N1 + N2 + ...Nn	[10]
Stream length (Ls)	Ls = L1 + L2 + ...+ Ln	[11]
Bifurcation ratio (Rb)	Rb = Nu/Nu + 1, where Nu is the number of streams of any given order, and Nu + 1 presents the number for the next higher order.	[22]
Basin Area (A)	Projected area enclosed by sub-basin boundary	[10]
Basin Perimeter (P)	Horizontal projection of the length of basin divide	[10]
Elongation ratio (Re)	Dc/Lb	[22]
Circularity ratio (Rc)	$Rc = 4\pi A/P^2$	[11]
Shape factor (Sh-f)	Sh-f = 1/Ff	[10,23]
Drainage density (Dd)	Dd = Lu/A	[10,24]
Stream frequency (Fs)	F = Nu/A	[10]
Drainage texture (Dt)	Dt = Nu/P	[10]

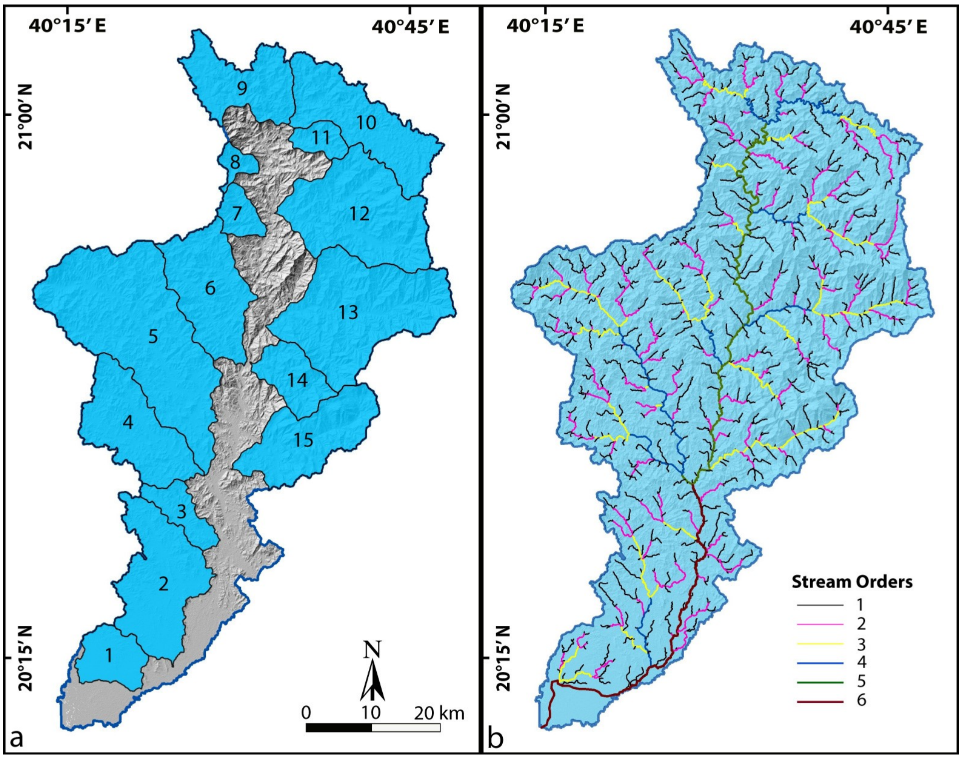

Figure 4. (**a**) sub-catchments (1–15) and (**b**) different stream orders of the Wadi Al-Lith watershed.

The maximum (Xmax) and minimum (Xmin) values of each parameter for every sub-catchment were identified. Since the selected morphometric parameters for each sub-basin were measured in different units, they were standardized through normalization. The morphometric risk assessment factor (MRAF) score for Group 1 parameters was computed using Equation (1), and for Group 2 parameters, using Equation (2) [4]:

$$\text{Risk value} = 4 \times (X - X\text{min})/(X\text{max} - X\text{min}) + 1 \quad (1)$$

$$\text{Risk value} = 4 \times (\text{X} - \text{Xmax})/(\text{Xmin} - \text{Xmax}) + 1 \tag{2}$$

In these formulas, X represents the value of the parameter, while Xmin. and Xmax. refer to the minimum and maximum values of the parameter within the dataset. This process resulted in normalized values that represent the relative risk associated with each morphometric parameter in comparison to the same parameter across other sub-basins. The calculated MRAF score falls between 1 and 5. For Group 1 parameters, a score of 5 signifies a higher flood risk, while a score of 1 represents a lower risk. Conversely, for Group 2 parameters, a score of 5 indicates a lower risk, and a score of 1 signifies a higher risk. Based on the classification applied in Ref. [4], the total ranking score for each catchment's parameters was calculated and categorized into three susceptibility levels: low flooding susceptibility (scores ranging from 27 to 35), moderate flooding susceptibility (scores from 36 to 44), and high flooding susceptibility (scores above 45). Thus, a flash flood susceptibility map for the Wadi Al-Lith watershed was developed.

In contrast to the morphometric ranking method, the author of Ref. [25] analyzed the connection between the bifurcation ratio (Rb), drainage density (Dd), and stream frequency (Fs) to assess flash flood risk. By plotting Rb against Dd and Rb against Fs, he identified relationships that helped evaluate flood risk across different sub-basins. The resulting graphs of Dd versus Rb and Dd versus Fs revealed two curves that divided the basins into three zones. Zone A included basins with a low bifurcation ratio but high drainage density and stream frequency, indicating a high flash flood potential. Zone B consisted of basins with a moderate bifurcation ratio and medium to high drainage density and stream frequency, suggesting a moderate flash flood risk. Zone C contained basins with a high bifurcation ratio and low to medium drainage density and stream frequency, reflecting a lower likelihood of flash floods.

4. Results and Discussion

Extensive numerical and field-based research has been carried out to explore the evolution of drainage networks in response to natural hazards such as seismic events, floods, and soil erosion [20–24]. Morphometric analysis offers valuable insights into the characteristics of landscapes and landforms, shedding light on their natural dynamics. Evaluating the areal and linear morphometric aspects of catchments helps to better understand and assess the geomorphological and hydrological conditions within watersheds [24,26–28]. A thorough and integrated modeling of morphometric outcomes can assist policymakers in formulating effective development strategies, especially concerning water resource management and soil erosion prevention. The results of the morphometric analysis applied to the Wadi Al-Lith watershed and its fifteen sub-catchments are summarized in Table 2. The assessment of the primary river in the Wadi Al-Lith basin reveals that it is a 6th-order river. The total length of the studied sub-basins is estimated at 1502.7 km, with an average bifurcation ratio of around 35.123 and a total of 932 stream segments. Larger basins can capture and retain more precipitation than smaller basins. This greater capacity often results in a pronounced peak discharge during rainfall events, which is critical in assessing flood risks. Moreover, the size and shape of these basins influence various hydrological metrics, including stream order, stream density, and the dimensions of the basin itself (length, width, and perimeter), all of which contribute to the overall dynamics of runoff.

Generally, the hydrological response of any watershed is intricately linked to its runoff generation, which is controlled by multiple factors, including basin morphology, geological structure, soil composition, and land use/land cover, while the morphometric characteristics determine the distribution of surface runoff. Specifically, stream order, which is an indicator of the stream network hierarchy, plays a key role in water flow dynamics. As stream order increases, there is a greater concentration of water within the channels, amplifying runoff volumes and elevating the potential for flash floods [4,7,26–28]. In higher-order streams, the capacity to carry large amounts of water increases significantly, often contributing to more severe flood events.

Table 2. Morphometric parameter values for the 15 sub-catchments of the Wadi Al-Lith watershed.

MP	**Sc-1**	**Sc-2**	**Sc-3**	**Sc-4**	**Sc-5**	**Sc-6**	**Sc-7**	**Sc-8**	**Sc-9**	**Sc-10**	**Sc-11**	**Sc-12**	**Sc-13**	**Sc-14**	**Sc-15**
Lb	10.89	27.18	14.42	21.22	39.31	21.22	8.27	6.21	18.59	22.99	8.61	23.63	28.48	12.43	24.24
Wb	7.05	8.21	3.76	8.87	11.65	8.96	4.75	3.50	7.85	8.84	4.12	11.76	11.51	6.65	7.33
Rlw	1.54	3.31	3.83	2.39	3.37	2.36	1.74	1.77	2.36	2.6	2.08	2	2.47	1.86	3.3
Os	5	4	3	4	4	4	3	3	4	5	3	3	3	3	3
Ns	36	73	17	83	161	69	9	7	53	72	15	103	123	31	65
Ls	52.95	137.40	30.76	118.37	273.28	109.62	18.43	12.47	91.35	134.56	21.03	158.92	179.31	44.86	99.41
Rb	1.91	2.41	1.31	2.47	3.86	2.70	1.41	0.85	1.88	2.17	1.36	3.38	3.66	1.96	2.47
A	76.83	223.28	54.32	188.40	458.20	190.92	39.30	21.75	146.08	203.51	35.57	278.09	328.08	82.09	177.71
P	40.13	92.61	41.3	76.12	118.5	70.32	27.68	25.59	77.53	93.55	25.96	82.21	89.43	41.74	71.77
Re	1.09	0.63	0.39	0.52	0.51	0.46	0.77	1.19	0.81	0.48	0.54	0.81	0.77	0.53	0.45
Rc	1.21	2.59	3.00	1.87	2.64	1.85	1.36	1.39	1.85	2.03	1.63	1.57	1.94	1.45	2.59
Sh-f	1.54	3.30	3.82	2.39	3.37	2.36	1.74	1.77	2.36	2.59	2.08	2.00	2.47	1.85	3.30
Dd	0.68	0.61	0.56	0.62	0.59	0.57	0.46	0.57	0.62	0.66	0.59	0.57	0.54	0.54	0.60
Fs	4.68	3.26	3.12	4.40	3.51	3.62	2.28	3.21	3.67	3.53	4.21	3.70	3.74	3.77	3.65
Dt	0.89	0.78	0.41	1.09	1.35	0.98	0.32	0.27	0.68	0.76	0.57	1.25	1.37	0.74	0.90

Upon examining Table 2, it becomes clear that sub-catchments sc-1 and sc-10 are classified with the highest stream orders, reaching the 5th order. This suggests that these sub-basins may experience higher water retention and runoff during rainfall events, making them more vulnerable to flash flooding. On the other hand, sub-catchments sc-2, sc-4, sc-5, sc-6, and sc-9, which have lower stream orders (4th order), are less prone to rapid water concentration in their channels. The total number of streams within a basin, which reflects the drainage capacity of the landscape, is influenced by the basin's underlying lithology, soil texture, and precipitation patterns. A greater number of streams generally increases the speed at which water is discharged from the basin, contributing to the rapid runoff process [2,29]. Sub-catchment sc-5 has the highest number of streams, totaling 161, indicating a dense drainage network capable of rapid water conveyance. In contrast, sub-catchment sc-8, with only seven streams (Table 2; Figure 5), suggests a less complex drainage pattern, which may affect both water retention and flood response. These variations highlight how different sub-catchments respond to hydrological processes, ultimately influencing their susceptibility to flash flooding.

Drainage density is a key hydrological metric that reflects the ratio of the total length of streams and rivers within a basin to the basin's surface area, a concept first defined in Ref. [10]. This characteristic is strongly governed by several factors, including the infiltration capacity of the soil and underlying rock formations, the geological structure, the amount of vegetation cover, and the overall topographical relief of the watershed. Higher drainage density often signals a reduced ability for water to percolate into the ground, leading to an increased potential for surface runoff [27]. This in turn suggests a greater likelihood of erosion, as the runoff can more easily strip soil and sediment from the surface, contributing to the basin's susceptibility to erosion. Additionally, it reflects the overall efficiency of the drainage network in removing water from the landscape. The degree to which a landscape is dissected by streams and rivers is closely related to the interplay of several key factors, such as the type and density of vegetation cover, the physical and chemical properties of the soil, the geomorphological characteristics of the basin, and the underlying geology. Rainfall patterns and intensity also play a crucial role, as more frequent or intense rainfall can accelerate the development of drainage networks and increase the potential for runoff. In catchments with less vegetation or more impermeable surfaces, water tends to move quickly across the landscape, resulting in a denser drainage network. In the specific case of the Wadi Al-Lith watershed, drainage density values vary across different sub-catchments. For instance, sub-basin sc-7 exhibits a drainage density of 0.46, while sub-catchment sc-1 has a higher value of 0.68 (Table 2; Figure 5). These variations suggest a moderate to high likelihood of surface runoff, with the higher values indicating areas where water retention is low and runoff processes dominate. Such areas are typically more prone to flash floods and erosion, as the landscape's ability to absorb rainfall is limited. The differing drainage densities across sub-basins highlight the complex interplay of topography, geology, and hydrology that shapes the watershed's overall vulnerability to flooding and erosion.

Stream frequency is a key parameter in hydrological studies, indicating the number of stream segments present per unit area in a watershed. This concept, originally proposed in Ref. [10], is a useful indicator of the drainage network's complexity. Higher stream frequency values often suggest a more intricate drainage system, which can lead to faster surface runoff during rainfall events. This is because basins with numerous streams tend to collect and channel water more rapidly, increasing the potential for flash flooding [30]. In the case of the Wadi Al-Lith watershed, the stream frequency varies across different sub-catchments, with the highest value observed in sub-catchment sc-1 at 4.68, indicating a dense stream network. On the other hand, sub-catchment sc-7 has the lowest frequency at 2.28, suggesting a sparser stream network and potentially lower runoff response.

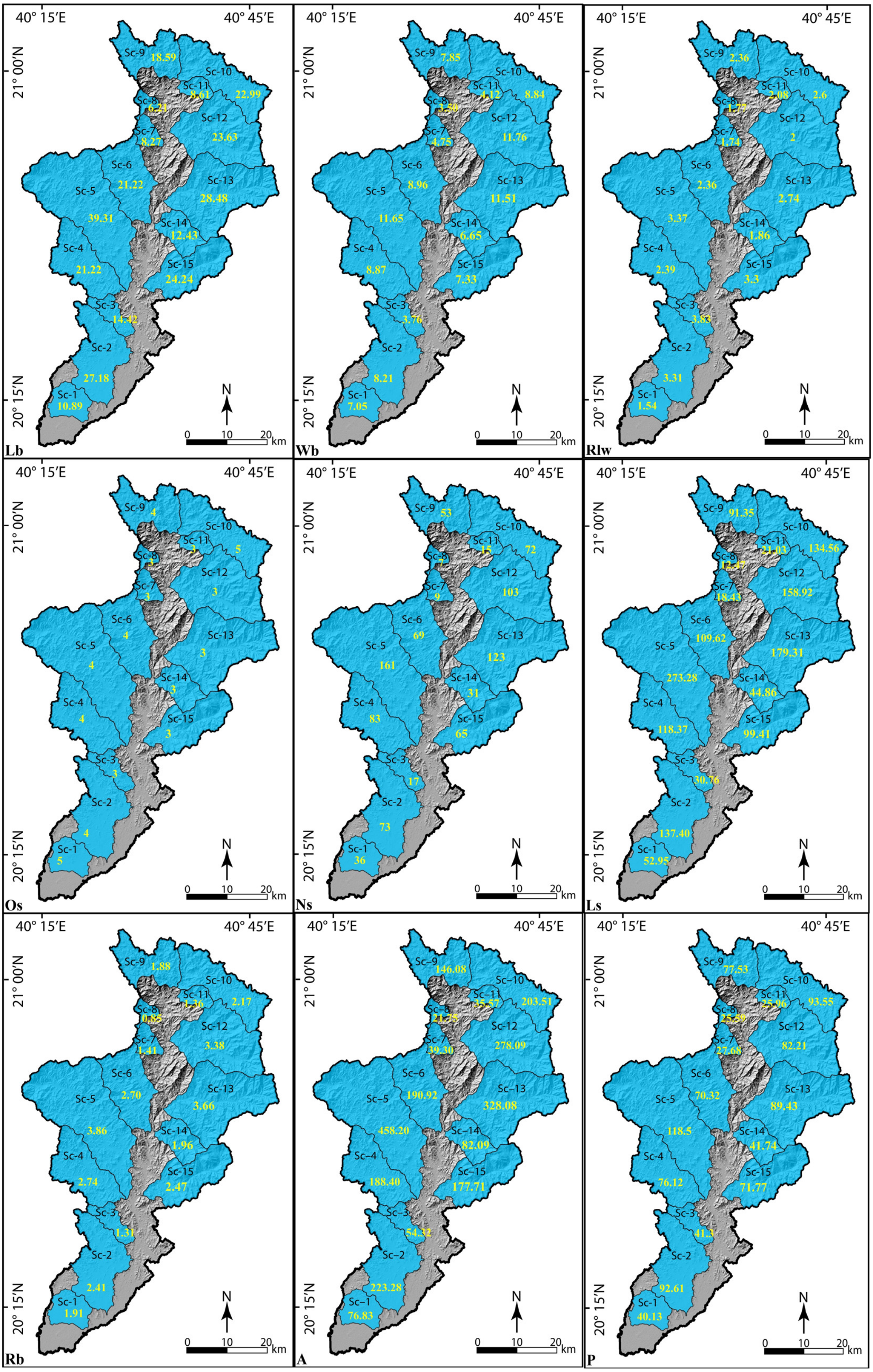

Figure 5. *Cont.*

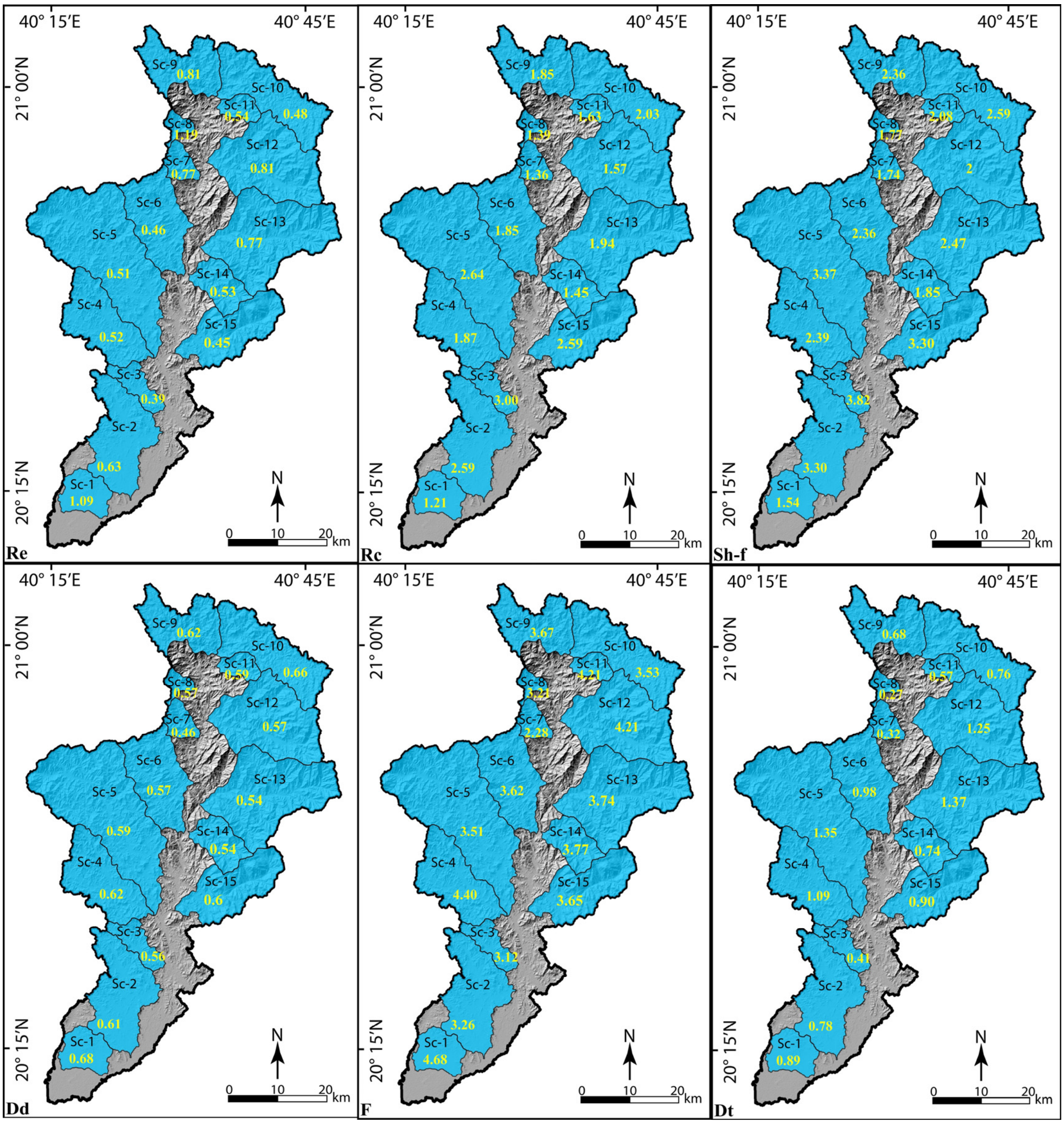

Figure 5. Distribution of the morphometric parameter values for the 15 sub-catchments. Lb: basin length; Wb: basin width; Rlw: length width ratio; Os: stream order; Ns: stream number; Ls: stream length; Rb: bifurcation ratio; A: total area; P: perimeter; Re: elongation ratio; Rc: circulation ratio; sh-f: shape factor; Dd: drainage density; F: stream factor; Dt: stream texture.

The bifurcation ratio is another critical factor that sheds light on the branching patterns of stream networks within a basin. It represents the ratio of the number of streams in a lower order to those in the next higher order, providing insights into the structure of the drainage system. A high bifurcation ratio indicates a more complex branching pattern, while a low ratio suggests a simpler one. In this study, sub-catchment sc-5 exhibits the highest bifurcation ratio at 3.86, pointing to a highly branched stream network. Conversely, sub-catchment sc-8 has the lowest bifurcation ratio at 0.85, which could mean that water flows more directly into a few main channels (Table 2; Figure 5). Lower bifurcation ratios are often associated with a higher risk of flash flooding, as they imply that water converges into fewer, larger channels, increasing the likelihood of sudden peak discharges during heavy rainfall [9].

Drainage texture, which refers to the relative spacing of streams within a basin, is largely determined by the characteristics of the underlying soil, rock formations, and surface features. It reflects the interaction between the physical properties of the landscape and the hydrological processes at play. A fine drainage texture is typically found in areas with soft, permeable soil and minimal vegetation cover, allowing water to spread across numerous smaller channels. In contrast, coarse drainage texture is more common in regions with hard, impermeable surfaces, where water flows over fewer, widely spaced channels [23]. According to the classification of Ref. [31], drainage texture ranges from very coarse (<2) to very fine (>8). In the Wadi Al-Lith watershed, the drainage texture varies significantly across sub-catchments. Significantly, the 15 sub-catchments give values less than 2 falling into the very coarse category, suggesting relatively wider stream spacing and less surface runoff (Table 2; Figure 5).

The shape factor of a drainage basin serves as a critical indicator of its hydrological behavior and is primarily influenced by the length of the main watercourse and the overall perimeter of the basin. The morphological characteristics of the landscape, along with the geological composition beneath the surface, play a significant role in shaping the basin's form [32,33]. As presented in Table 2, sub-catchment sc-8 exhibits the highest shape factor of 3.82, suggesting a relatively compact configuration, while sub-catchment sc-1 has the lowest shape factor at 1.54. This lower shape factor indicates that sc-1 has a more elongated profile, which is often associated with increased surface runoff potential, heightening the risk of flooding during intense rainfall events. An elongated basin shape typically allows for faster water flow, reducing the time available for infiltration into the soil and increasing the likelihood of rapid runoff. Another important metric for assessing basin geometry is the elongation ratio, which provides a numerical representation of the basin's shape and helps evaluate the flow dynamics and resistance of the terrain [23]. In this study, sub-catchment sc-9 shows the highest elongation ratio of 1.19, suggesting a near-circular basin shape that is conducive to efficient water flow and drainage. Conversely, sub-catchment sc-3 records a lower elongation ratio of 0.39, indicating a more elongated shape. The classification system used in Ref. [11] categorizes elongation ratios into five distinct types: circular (>0.9), oval (0.8–0.9), slightly elongated (0.7–0.8), elongated (0.5–0.7), and highly elongated (<0.5). Basins with high elongation ratios, particularly those close to 1, tend to have a more circular profile. Such shapes are commonly found in regions with steep gradients, where the rapid descent of water increases the likelihood of flash flooding due to the swift transport of water towards the basin outlet [4].

The implications of these geometric characteristics extend beyond mere definitions, as they influence the overall hydrological response of the basin. Understanding the shape factor and elongation ratio can aid in predicting how water will behave during storm events, guiding effective flood management and mitigation strategies. Furthermore, these metrics provide valuable insights into the erosion potential and sediment transport capabilities of the basin, crucial for land-use planning and environmental conservation efforts in the Wadi Al-Lith watershed. By integrating these parameters into hydrological models, researchers and policymakers can enhance their understanding of the basin's dynamics and better prepare for potential flood hazards.

The circulatory ratio serves as a crucial geomorphological characteristic of a watershed, playing a significant role in evaluating both the efficiency of drainage systems and the associated risk of flash flooding. This ratio provides insight into how water moves through a basin, which can vary considerably based on the basin's shape. Typically, in basins that exhibit a circular or rounded geometry, runoff is more uniformly distributed across the landscape. As a result, water tends to travel similar distances simultaneously, leading to the possibility of it reaching the basin outlet concurrently during heavy rainfall events. This synchronous arrival often causes a sharp increase in peak discharge, heightening the potential for flash flooding. In contrast, elongated basins have their outlets located on one extreme side of the main stream. In these configurations, runoff tends to be dispersed over a longer period, leading to a gradual release of water into the outlet and resulting in a lower peak discharge. This distinction in flow behavior can significantly impact the flood risk profile of different sub-basins. In our analysis, sub-catchment sc-3 demonstrates the highest circulatory ratio of 3, indicating a more circular form that is likely to produce higher runoff potential. Conversely, sub-catchment sc-1 has a much lower circulatory ratio of 1.21, suggesting a more elongated shape and a consequently lower risk of flash flooding. A high circulatory ratio generally correlates with increased runoff potential, while a lower ratio reflects reduced flooding risks, as supported by the findings in Ref. [4].

The evaluation of flash flood risks through morphometric hazard analysis (MHA) has identified sub-catchments sc-2, sc-4, sc-5, sc-6, sc-10, sc-12, sc-13, and sc-15 as areas with a high vulnerability to flash flooding events (Figure 6). This finding suggests a critical need for monitoring and management strategies in these regions. Sub-catchments sc-1 and sc-9, which have basin areas of 76.83 and 146.08 square kilometers, respectively, exhibit a moderate level of susceptibility (Figure 6). These sub-catchments may experience flooding under specific conditions, particularly during heavy rainfall events. Additionally, sub-catchments sc-3, sc-7, sc-8, and sc-14 reflect a low level of flood susceptibility. Among the various morphometric factors analyzed, the elongation ratio of the basin area (A) emerges as a pivotal characteristic that plays a significant role in shaping the runoff dynamics within the watershed. The elongation ratio helps determine how quickly water can flow through the basin, influencing how runoff accumulates and contributes to flash flood potential. Research has consistently highlighted the importance of basin area in models assessing flash flood susceptibility, confirming its relevance in predicting flood behavior and risk [24,32]. A particularly noteworthy aspect of the flash flood susceptibility map developed using the MRA approach (illustrated in Figure 6) is the observation that streams flowing into the Wadi Al-Lith watershed from the eastern and western catchment areas generally show a higher risk of flash flooding, while the northern and southern catchment areas provide the conditions for moderate flood susceptibility. The differences in flash flood risk between these regions can be attributed to variations in topography, land use, vegetation cover, and hydrological processes, all of which influence how rainfall is absorbed and drained within the watershed. Understanding these dynamics is essential for developing effective flood management strategies and mitigation measures. Identifying high-risk areas allows for targeted interventions, such as improving drainage infrastructure, implementing land-use planning, and enhancing community preparedness programs, ultimately reducing the impact of flash floods on local populations and ecosystems.

Sub-catchments sc-2, sc-4, sc-5, sc-6, sc-10, sc-12, sc-13, and sc-15 demonstrate significant vulnerability to flash flooding, attributed to a confluence of key hydrological characteristics. Sub-catchments sc-2, sc-4, sc-5, and sc-6 are classified as 4th-order streams, while sub-catchments 10 is assigned to 5th-order streams. Additionally, sub-catchments sc-12, sc-13, and sc-15 are classified as 3rd-order streams. The extensive stream lengths measuring 137.40 km for sc-2, 118.37 km for sc-4, 273.28 km for sc-5, 109.62 km for sc-6, 134.56 km for sc-10, 158.92 km for sc-12, 179.31 km for sc-13, and 99.41 km for sc-15 indicate a well-developed drainage network that can rapidly transport water during intense rainfall events. Additionally, these sub-catchments exhibit considerable basin lengths of 27.18 km, 21.22 km, 39.31 km, 21.22 km, 22.99 km, 28.48 km, and 24,24 km, respectively, further enhancing their capacity to channel runoff towards lower elevations. The drainage frequency for sc-2, sc-4, sc-5, sc-6, sc-10, sc-12, sc-13, and sc-15 reflects the number of streams per unit area, which contributes to the effective movement of water through the landscape. While the stream densities remain moderate, with values of 0.46 for sc-7, this metric suggest an adequately interconnected system that can lead to rapid accumulation and flow of water during storm events. The low elongation ratios of the high flood susceptibility sub-catchments indicate a more rounded basin shape. This geometry is critical, as it typically promotes quicker runoff because water from various points within the basin can reach the outlet simultaneously. Additionally, the shape factor values for these sub-catchments are relatively low suggesting that the sub-catchments are more efficient at funneling water toward the outlet, further increasing the likelihood of flash floods. In contrast, a small cohort of sub-catchments, including sc-3, sc-7, sc-8, sc-11, and sc-14, accounts for approximately 9.3% of the total sub-catchments and exhibits lower susceptibility to flooding risks. These areas are characterized by more favorable morphometric traits, such as a lower number of streams and less extensive drainage networks, which collectively contribute to a reduced capacity for rapid runoff. Meanwhile, sub-catchments sc-1 and sc-9 represent around 8.9% of the total sub-catchments and display moderate flood susceptibility. While these areas are at some risk, their morphometric features, including a mix of elongation ratios and drainage densities, render them less vulnerable than the high flood susceptibility sub-catchments. The flood susceptibility mapping, as depicted in Figure 6 and Table 3, utilizes morphometric hazard analysis (MHA) to illustrate the varied levels of flood risk among the sub-basins within the Swat River watershed. This visual representation underscores the importance of understanding these morphometric parameters, as they play a pivotal role in assessing the potential impact of flash floods and informing land management and disaster preparedness strategies in the region.

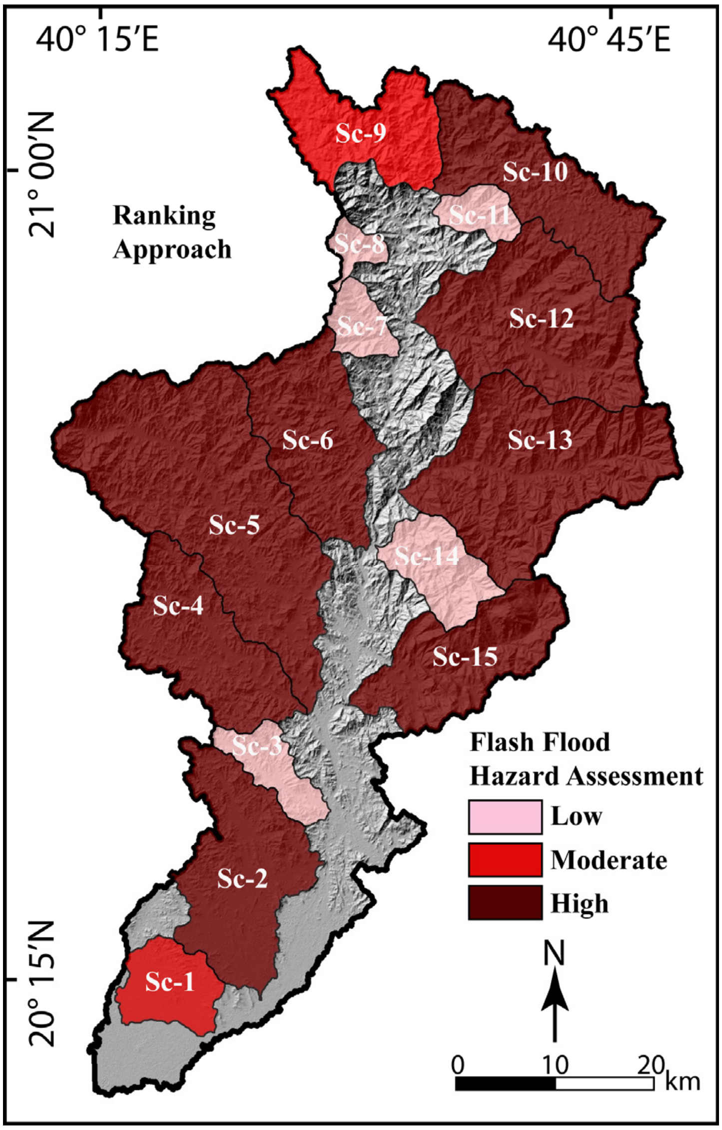

Figure 6. Flood susceptibility levels based on the ranking hazard approach.

Table 3. Ranking of the morphometric parameters of the 15 sub-catchments of the Wadi Al-Lith watershed.

MP	**Sc-1**	**Sc-2**	**Sc-3**	**Sc-4**	**Sc-5**	**Sc-6**	**Sc-7**	**Sc-8**	**Sc-9**	**Sc-10**	**Sc-11**	**Sc-12**	**Sc-13**	**Sc-14**	**Sc-15**
Lb	1.56	3.53	1.99	2.81	5.00	2.81	1.25	1.00	2.50	3.03	1.29	3.11	3.69	1.75	3.18
Wb	2.71	3.28	1.12	3.60	4.95	3.64	1.61	1.00	3.11	3.59	1.30	5.00	4.88	2.53	2.85
Rlw	0.49	5	6.32	2.66	5.15	2.58	1.00	1.08	2.58	3.19	1.87	1.66	2.86	1.31	4.97
Os	5	3	1	3.00	3.00	3.00	1.00	1.00	3.00	5.00	1.00	1.00	1.00	1.00	1.00
Ns	1.75	2.71	1.25	2.97	5.00	2.61	1.05	1.00	2.19	2.69	1.21	3.49	4.01	1.62	2.51
Ls	1.62	2.91	1.28	2.62	5.00	2.49	1.09	1.00	2.21	2.87	1.13	3.25	3.56	1.50	2.33
Rb	2.40	3.07	1.61	3.15	5.00	3.46	1.74	1.00	2.37	2.75	1.68	4.36	4.73	2.48	3.15
A	1.71	3.63	1.42	3.18	6.70	3.21	1.23	1.00	2.62	3.37	1.18	4.35	5.00	1.79	3.04
P	1.62	3.88	1.67	3.18	5.00	2.93	1.09	1.00	3.24	3.93	1.02	3.44	3.75	1.70	2.99
Re	1.5	3.8	5	4.35	4.40	4.65	3.10	1.00	2.90	4.55	4.25	2.90	3.10	4.30	4.70
Rc	1	4.86	6	2.85	5.00	2.79	1.42	1.50	2.79	3.29	2.17	2.01	3.04	1.67	4.86
Sh-f	5	1.91	1	3.51	1.79	3.56	4.65	4.60	3.56	3.16	4.05	4.19	3.37	4.46	1.91
Dd	5	3.72	2.81	3.91	3.36	3.00	1.00	3.00	3.91	4.64	3.36	3.00	2.45	2.45	3.55
Fs	5	1	0.60	4.21	1.70	2.01	−1.76	0.86	2.15	1.76	3.68	2.24	2.35	2.44	2.10
Dt	3.25	2.85	1.50	3.98	4.93	3.58	1.18	1.00	2.49	2.78	2.09	4.56	5.00	2.71	3.29
Sum.	39.65	49.18	34.63	49.98	65.98	46.33	20.65	21.04	41.62	50.60	31.28	48.56	52.80	33.69	46.43
RMHD	2	1	3	1	1	1	3	3	2	1	3	1	1	3	1

El-Shamy's approach highlights key morphometric parameters, including the bifurcation ratio, drainage density, and stream frequency, which are essential in assessing flash flood susceptibility. Figure 7a,b display the ranking of flash flood susceptibility for the sub-catchments of the Swat River basin, based on this methodology. By analyzing the relationship between drainage density and bifurcation ratio, the study reveals that sub-catchments sc-1:4, sc-6:12, sc-14, and sc-15, which account for 68.6% of the total sub-catchments, have drainage densities of 0.86, 0.61, 0.56, 0.62, 0.57, 0.46, 0.57, 0.62, 0.59, 0.57, 0.54, and 0.6, combined with bifurcation ratios of 1.91, 2.41, 1.31, 2.47, 2.7, 1.41, 0.85, 1.88, 2.17, 1.36, 3.38, 1.96, and 2.47, respectively. These values classify these sub-catchments as highly vulnerable to flash flooding, indicating a greater likelihood of water accumulation and runoff during extreme rainfall events. In contrast, the remaining two sub-catchments, including sc1 through sc-15, and sc-17, representing 31.4% of the total sub-catchments, are categorized as having moderate flash flood susceptibility. This suggests that while these sub-catchments may still experience flooding, their morphometric characteristics make them less prone to severe flash flood impacts compared to the highly susceptible areas.

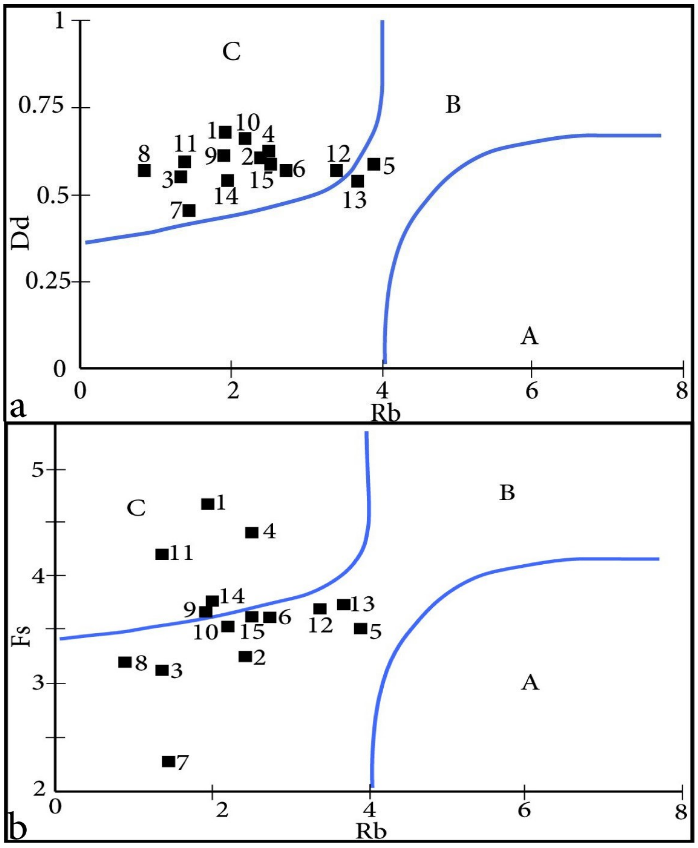

Figure 7. El-Shamy method diagrams for assigning flash flood susceptibility classes. (**a**) Bifurcation ratio (Rb) against drainage density (Dd) and (**b**) bifurcation ratio (Rb) against stream frequency (Fs).

Additionally, an assessment based on the relationship between stream frequency and bifurcation ratio further refines the flash flood risk analysis. Sub-catchments sc-1, sc-4, sc-9, sc-10, and sc-14, which constitute 27.83% of the total sub-catchments, indicate the highest susceptibility to flash flooding. This combination suggests that these sub-catchments have a denser network of streams and a more fragmented drainage system, leading to higher runoff potential during heavy rainfall. On the other hand, the remaining 11 sub-catchments, including sc-2 to sc-3, sc5:8 to sc-11:13, and sc15, demonstrate overall moderate flash flood susceptibility. This indicates that these areas, while not immune to flash flooding, possess morphometric characteristics that mitigate extreme flood risks to some extent. Figures 7 and 8 provide a comprehensive visual representation of the flash flood susceptibility rankings for the Wadi Al-Lith sub-catchments, derived from the relationships between drainage density, stream frequency, and bifurcation ratio. These rankings highlight critical areas that require further flood management and mitigation strategies.

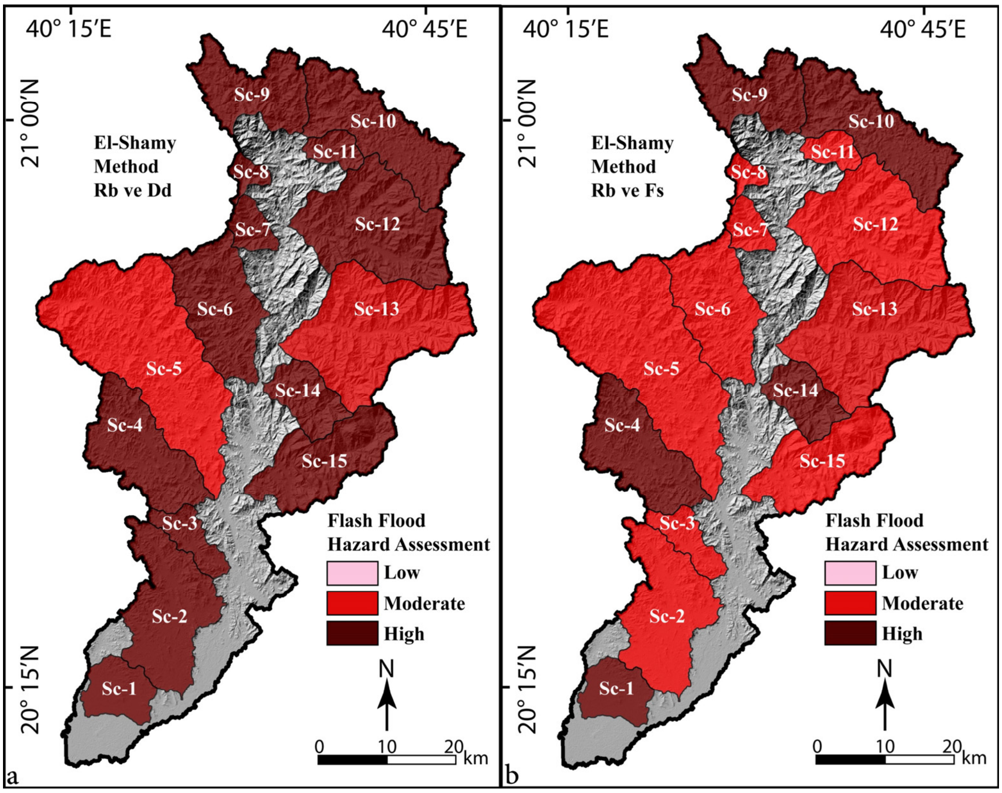

Figure 8. Flood susceptibility levels according to the El-Shamy method. (**a**) Rb ve Dd and (**b**) Rb ve Fs.

In this study, the El-Shamy method was employed to assess the flash flood susceptibility of 15 sub-catchments within the Wadi Al-Lith watershed, Saudi Arabia. The analysis revealed that there is a match between eight sub-catchments, indicating a consistency in the results when considering key morphometric parameters such as the bifurcation ratio, drainage density, and stream frequency. This matching suggests that these sub-catchments exhibit similar hydrological and geomorphological characteristics, leading to a coherent classification in terms of flash flood risk. On the other hand, the remaining seven sub-catchments did not match, showing a divergence in the susceptibility ranking. The differentiation between matching and non-matching sub-catchments may be attributed to several factors. One potential reason could be the variation in the topographic complexity and geological structure within the watershed. Sub-catchments with more homogeneous terrain and geological features tend to produce more consistent results, while those with more diverse or fragmented terrain may behave differently in terms of drainage response. Additionally, anthropogenic factors, such as land use changes, urbanization, or alterations in the natural drainage systems, may also play a role in creating inconsistencies, particularly in areas where natural flood pathways have been disrupted.

Moreover, discrepancies could arise from differences in the scale of morphometric parameters between the sub-catchments. For example, variations in drainage network patterns or stream density can lead to localized differences in flash flood susceptibility, even when other morphometric indicators remain comparable. These factors highlight the importance of conducting detailed, site-specific analyses to account for the spatial variability in flash flood risk within the Wadi Al-Lith watershed.

5. Conclusions

This study provides a detailed and systematic evaluation of flash flood hazards within the Wadi Al-Lith watershed by integrating morphometric analysis with a comparative assessment through the morphometric ranking approach and El-Shamy's method. Through the analysis of 15 morphometric parameters derived from high-resolution ALOS PALSAR DEM data (12.5 m), the study identified notable differences in flood susceptibility among the sub-catchments. The morphometric analysis classified sub-catchments SC-2, SC-4, SC-5, SC-6, SC-10, SC-12, SC-13, and SC-15 as having a high risk of flash flooding, while others, such as SC-8 and SC-9, exhibited moderate levels of vulnerability. By employing both the morphometric ranking approach and El-Shamy's method, the study has provided a comprehensive dual analysis, with each method offering distinct insights into the flood risk profile of the watershed. The morphometric ranking method, which considers basin-specific features such as drainage density, bifurcation ratio, and basin shape, provided a robust framework for identifying areas most prone to flash floods. El-Shamy's method, on the other hand, presented an alternative prioritization of sub-catchments, highlighting differences in the ranking of flood hazards and underscoring the complexity of flood risk assessment.

The comparison between the two approaches revealed the advantages of employing morphometric parameters for a more accurate reflection of flood risk. Given the alignment between the results of the morphometric analysis and the region's known hydrological behavior, it became clear that this method may offer a more reliable basis for flood risk mitigation. However, El-Shamy's method adds value by offering a different perspective, enabling a more nuanced understanding of risk prioritization when used alongside morphometric approaches. The insights gained from this study are critical for enhancing flood risk management in arid regions like Wadi Al-Lith, where flash floods pose a recurring threat. The hazard maps generated from this analysis will serve as essential tools for regional planners and authorities, enabling more informed decision-making regarding flood mitigation and disaster preparedness. These maps highlight areas of heightened vulnerability, where preventive measures such as flood control infrastructure, early warning systems, and land-use planning can be strategically focused to minimize future risks.

To further improve flood hazard assessments, this study emphasizes the importance of incorporating data with greater spatial resolution and on-the-ground verification. The techniques applied in this study show how remote sensing and GIS technology can be integrated to evaluate flash flood hazards at the sub-catchment level, yielding precise information that can be utilized to guide local planning initiatives. Future studies can look at also incorporating climate change lessons to know more about how changes in precipitation systems could affect the region's risk of flooding.

In summary, this research provides important insights for local administrators, planners, and decision-makers in addition to more advancing understanding of flash flood threats within the Wadi Al-Lith watershed. The results of this study enable these stakeholders to better allocate resources and effectively prioritize risk mitigation measures by knowing the locations of high flood susceptibility. Environmental planners can utilize this valuable information, for example, to guide zoning laws and steer development away from regions that pose a high danger. To enhance community readiness, decision-makers could provide decisions to implement early warning systems in areas that are more susceptible. Additionally, to better protect both financial assets and human lives, the results also aid the creation of targeted infrastructure expenditures, including enhanced drainage patterns or flood barriers in important flood-prone regions. Ultimately, the current study creates a proactive flood management paradigm.

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B.B. and A.A.; supervision, B.B. and A.A.; project administration, B.B. and A.A.; funding acquisition, B.B. and A.A. All authors have read and agreed to the published version of the manuscript.

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References

1. Shah, S.M.H.; Yassin, M.A.; Abba, S.I.; Lawal, D.U.; Al-Qadami, E.H.H.; Teo, F.Y.; Mustaffa, Z.; Aljundi, I.H. Flood Risk and Vulnerability from a Changing Climate Perspective: An Overview Focusing on Flash Floods and Associated Hazards in Jeddah. *Water* **2023**, *5*, 3641. [CrossRef]
2. Dhiman, R.; VishnuRadhan, R.; Eldho, T.I.; Inamdar, A. Flood risk and adaptation in Indian coastal cities: Recent scenarios. *Appl. Water Sci.* **2019**, *9*, 5. [CrossRef]
3. Arabameri, A.; Saha, S.; Chen, W.; Roy, J.; Pradhan, B.; Bui, D.T. Flash flood susceptibility modelling using functional tree and hybrid ensemble techniques. *J. Hydrol.* **2020**, *587*, 125007. [CrossRef]
4. Nasir, M.J.; Iqbal, J.; Ahmad, W. Flash flood risk modeling of swat river sub-watershed: A comparative analysis of morphometric ranking approach and El-Shamy approach. *Arab. J. Geosci.* **2020**, *13*, 1082. [CrossRef]
5. Fernández, D.; Lutz, M. Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. *Eng. Geol.* **2010**, *111*, 90–98. [CrossRef]
6. Khalifa, A.; Bashir, B.; Alsalman, A.; Naik, S.P.; Nappi, R. Remotely Sensed Data, Morpho-Metric Analysis, and Integrated Method Approach for Flood Risk Assessment: Case Study of Wadi Al-Arish Landscape, Sinai, Egypt. *Water* **2023**, *15*, 1797. [CrossRef]
7. Cotti, D.; Harb, M.; Hadri, A.; Aboufirass, M.; Chaham, K.R.; Libertino, A.; Campo, L.; Trasforini, E.; Krätzschmar, E.; Bellert, F.; et al. An Integrated Multi-Risk Assessment for Floods and Drought in the Marrakech-Safi Region (Morocco). *Front. Water* **2022**, *4*, 886648. [CrossRef]
8. Angillieri, M.Y.E. Morphometric characterization of the Carrizal basin applied to the evaluation of flash floods hazard, San Juan, Argentina. *Quat. Int.* **2012**, *253*, 74–79. [CrossRef]
9. Perucca, L.P.; Angilieri, Y.E. Morphometric characterization of del Molle Basin applied to the evaluation of flash floods hazard, Iglesia Department, San Juan, Argentina. *Quat. Int.* **2011**, *233*, 81–86. [CrossRef]
10. Horton, R.E. Erosional development of streams and their drainage basins; Hydrophysical approach to quantitative mor-phology. *Bull. Geol. Soc. Am.* **1945**, *56*, 275–370. [CrossRef]
11. Strahler, A.N. Quantitative geomorphology of drainage basins is channel networks. In *Applied Hydrology*; Chow, V., Ed.; McGraw Hill: New York, NY, USA, 1964; pp. 39–79.
12. Singh, W.R.; Barman, S.; Tirkey, G. Morphometric analysis and watershed prioritization in relation to soil erosion in Dudhnai Watershed. *Appl. Water Sci.* **2021**, *11*, 151. [CrossRef]
13. Khalifa, A.; Bashir, B.; Alsalman, A.; Bachir, H. Morphometric-hydro Characterization of the Coastal Line between El-Qussier and Marsa-Alam, Egypt: Preliminary Flood Risk Signatures. *Appl. Sci.* **2022**, *12*, 6264. [CrossRef]
14. Choudhari, P.P.; Nigam, G.K.; Singh, S.K.; Thakur, S. Morphometric based prioritization of watershed for groundwater potential of Mula river basin, Maharashtra, India. *Geol. Ecol. Landsc.* **2018**, *2*, 256–267. [CrossRef]
15. Bashir, B.; Alsalman, A. Morpho-Hydrological Analysis and Preliminary Flash Flood Hazard Mapping of Neom City, Northwestern Saudi Arabia, Using Geospatial Techniques. *Sustainability* **2024**, *16*, 23. [CrossRef]
16. Niyazi, B.; Khan, A.A.; Masoud Elfeki, A.; Basahi, J.; Zaidi, S. Morphological-hydrological relationships and the geo-morphological instantaneous unit hydrograph of Makkah Al-Mukarramah watersheds. *Arab. J. Geosci.* **2021**, *14*, 751. [CrossRef]
17. Hajam, R.A.; Hamid, A.; Bhat, S. Application of Morphometric Analysis for Geo-Hydrological Studies Using Geo-Spatial Technology –A Case Study of Vishav Drainage Basin. *J. Waste Water Treat. Anal.* **2013**, *4*, 1–12. [CrossRef]
18. Mesa, L.M. Morphometric analysis of a subtropical Andean basin (Tucumán, Argentina). *Environ. Geol.* **2006**, *50*, 1235–1242. [CrossRef]
19. Salvi, S.S.; Mukhopadhyay, S.; Ranade, S.D.; Rajagopalan, A. Morphometric Analysis of River Drainage Basin/Watershed using GIS and RS: A Review. *Int. J. Res. Appl. Sci. Eng. Technol.* **2017**, *5*, 503–508.
20. Bashir, B.; Alsalman, A. Geospatial Analysis for Tectonic Assessment and Soil Erosion Prioritization: A Case Study of Wadi Al-Lith, Red Sea Coast, Saudi Arabia. *Appl. Sci.* **2023**, *13*, 12523. [CrossRef]
21. Horton, R.E. Drainage-basin characteristics. *Trans. Am. Geophys. Union* **1932**, *13*, 350–361. [CrossRef]
22. Schumm, S.A. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bull. Geol. Soc. Am.* **1956**, *67*, 597–646. [CrossRef]
23. Bhatt, S.; Ahmed, S. Morphometric analysis to determine floods in the Upper Krishna basin using Cartosat DEM. *Geocarto Int.* **2014**, *29*, 878–894. [CrossRef]

24. Manzoor, Z.; Ehsan, M.; Khan, M.B.; Manzoor, A.; Akhter, M.M.; Sohail, M.T.; Hussain, A.; Shafi, A.; Abu-Alam, T.; Abioui, M. Floods and flood management and its socio-economic impact on Pakistan: A review of the empirical literature. *Front. Environ. Sci.* **2022**, *10*, 1021862. [CrossRef]
25. Shamy, E. Recent recharge and flash flooding opportunities in the Eastern Desert, Egypt. *Ann. Geol. Surv. Egypt* **1992**, *18*, 323–334.
26. Alqahtani, F.; Qaddah, A.A. GIS digital mapping of flood hazard in Jeddah–Makkah region from morphometric analysis. *Arab. J. Geosci.* **2019**, *12*, 199. [CrossRef]
27. Dube, K.; Nhamo, G.; Chikodzi, D. Flooding trends and their impacts on coastal communities of Western Cape Province, South Africa. *GeoJournal* **2022**, *87*, 453–468. [CrossRef]
28. Patton, P.C.; Baker, V.R. Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. *Water Resour. Res.* **1976**, *12*, 941–952. [CrossRef]
29. Mahmood, S.; Rahman, A.-U. Flash flood susceptibility modeling using geo-morphometric and hydrological approaches in Panjkora Basin, Eastern Hindu Kush, Pakistan. *Environ. Earth Sci.* **2019**, *78*, 43. [CrossRef]
30. Farhan, Y.; Anaba, O.; Salim, A. Morphometric Analysis and Flash Floods Assessment for Drainage Basins of the Ras En Naqb Area, South Jordan Using GIS. *J. Geosci. Environ. Prot.* **2016**, *4*, 9–33. [CrossRef]
31. Smith, K.G. Standards for grading texture of erosional topography. *Am. J. Sci.* **1950**, *248*, 655–668. [CrossRef]
32. Bapalu, G.V.; Sinha, R. GIS in Flood Hazard Mapping: A case study of Kosi River Basin, India. *GIS Dev. Wkly.* **2005**, *1*, 1–3.
33. Bathrellos, G.D.; Karymbalis, E.; Skilodimou, H.D.; Gaki-Papanastassiou, K.; Baltas, E.A. Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. *Environ. Earth Sci.* **2016**, *75*, 319. [CrossRef]