

Article

Flood Hazard and Risk Assessment of Flash Floods for Petra Catchment Area Using Hydrological and Analytical Hierarchy (AHP) Modeling

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Abstract: Floods are a widespread natural disaster that occur in most areas of the world, except for the polar regions. To minimize the damage caused by floods, effective management strategies and policies must be implemented. Petra and Wadi Musa areas are prone to floods, which happen every 2–3 years and result in significant harm to both lives and properties. To address this issue, a composite hazard and vulnerability index is commonly utilized to evaluate flood risk and guide policy formation for flood risk reduction. These tools are efficient and cost-effective in generating accurate results. Accordingly, the present study aims to determine the morphological and hydrometeorological parameters that affect flash floods in Petra catchment area and to identify high-risk zones using GIS, hydrological, and analytical hierarchy (AHP) modeling. Nine factors, including Elevation (E), Landuse/Landcover LULC, Slope (S), Drainage density (DD), Flood Control Points (FCP) and Rainfall intensity (RI), which make up the six risk indices, and Population Density (PD), Cropland (C), and Transportation (Tr), which make up the three vulnerability indices, were evaluated both individually and in combination using AHP in ArcGIS 10.8.2 software. These parameters were classified as hazard and vulnerability indicators, and a final flood map was generated. The map indicated that approximately 37% of the total area in Petra catchment is at high or very high risk of flooding, necessitating significant attention from governmental agencies and decision-makers for flood risk mitigation. The AHP method proposed in this study is an accurate tool for flood mapping that can be easily applied to other regions in Jordan to manage and prevent flood hazards.

Keywords: Petra; flash flooding; AHP; hydrological modelling; flood hazard and risk assessment



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1. Introduction

Flooding is one of the most common natural disasters worldwide, often causing destruction, damaging the physical environment and adversely affecting daily life and the local economy, leading to vulnerability on social and economic levels, mortality, community displacement and crop and infrastructure damage. Flooding can result from various factors, including heavy rainfall, storm surges, rapid snowmelt or dam failures. The severity of flooding is influenced by the intensity and duration of the precipitation, the landscape's ability to absorb water and existing drainage systems' capacity. Flooding is identified as a rise in water levels in coastal areas, reservoirs, streams and canals [1].

Rapid population growth and changes in land use are key factors increasing flood occurrences and human vulnerability globally. Climate change is expected to further escalate flood frequency and intensity, leading to significant economic losses and human fatalities. Currently, about 350 million people are affected by floods, and this number is projected to double by 2050, making floods a major environmental hazard. Studies have shown that southern, eastern, and southeastern Asia experience the deadliest floods, though the lethality has decreased over time due to improved resilience and risk reduction

strategies [2]. The rise in flood incidents is also linked to the conversion of land into water-resistant areas, causing erosion and natural rushing [3–5]. Between 2010 and 2019, the average annual loss from floods reached around USD 50 billion [6].

Updating flash flood management strategies is crucial for sustainable planning in any area. Effective flood risk management involves prioritizing appropriate flood control solutions. Multi-criteria decision-making (MCDM) and multi-criteria optimization and compromise solution methods have been employed to rank structural flood control options globally. These studies identify reservoir dams, retention basins and levees as the most effective solutions, whereas flood control gates and the no-project option are less favored. The findings highlight the importance of utilizing multiple MCDM methods for comprehensive evaluations, offering valuable insights for policymakers in resource allocation and the implementation of flood control measures [1].

Flash-flooding issues in Jordan have significantly escalated recently due to several factors, including ongoing changes in land use and land cover, inadequate enforcement of legislation, urban development, expansion in flood-prone areas and increasing urban density. Alongside the impacts of global climate change, these factors are expected to contribute to a rise in flood-related damages over time [7].

In the past several decades, severe flooding has taken place often in the Petra and Wadi Musa regions. An overview of these floods and their intensity are presented in Table 1. With a peak flow of 300 m³/s and a 100-year return time, the flood of 1963 is regarded as the worst flood ever. All Wadis received floodwater pour towards the main Wadi of the Wadi Mousa outflow during this incident due to the intense and unexpected rains. Most of the hydraulic infrastructure in the Wadi were obstructed by the huge sediment load of loose silt and sand that was transported by the flood.

Table 1. Summary of flash floods in the Wadi Musa and Petra areas.

Date	Flood	Flood Return Period
April, 1963	The water level reached an elevation of more than 10 m above the Wadi bed	100-year return period
December 1991	Flood water was about 10 m in some areas of the Siq passage	50-year return period
January, 1995	The water level reached an elevation of more than 12 m above the Wadi bed	10-year return period
November, 1996	the water level reached an elevation of more than 3 m above the Wadi bed	10-year return period
January, 2001	The water level reached an elevation of more than 3 m above the Wadi bed	10-year return period
May, 2018	The water level reached an elevation of more than 2 m above the Wadi bed	10-year return period
November, 2018	Flood water was about 3 m in some areas of the Siq passage	100-year return period

The Siq dam was also filled with sediment, causing flood water to overtop and enter the Siq instead of being diverted through the tunnel of Wadi Al-Mudhlim. Despite the great emergency efforts by Jordanian authorities to rescue trapped tourists in the Siq, 20 people lost their lives in this flood [8].

Due to the increasing risks and damages caused by floods, proper management and policies are essential to reduce the negative impact of this natural hazard. In the Petra and Wadi Musa areas, floods occur every 2–3 years, causing severe damage to both life and property. To effectively manage flood risk, a composite hazard and vulnerability index is widely recognized as a valuable tool that helps inform policy decisions aimed at reducing flood risk. This tool is both cost-effective and time-efficient, delivering accurate results.

In 1991, a flood occurred, estimated to have a return period of about 50 years, that destroyed two culverts upstream of the Siq and posed a significant challenge for tourists and visitors.

The City of Wadi Musa and Ancient City of Petra have been threatened by floods, with some notable events occurring in November 1996, which flooded the Siq entrance and necessitated the rescue of tourists. Unfortunately, deaths have also been recorded in the same area in more recent times [8].

Hydrologists have identified Wadi Musa flood as the highest risk and damage in Jordan due to its history of flooding. Therefore, a methodology is needed to predict flash floods in the area and find the best method to protect the urban areas from inundations. In this study, the WMS 11.2 software package was integrated with HEC-RAS [9] to prepare an inundation map (showing the extent and depth of inundation) within the Petra catchment area for floods of varying return periods.

Over the last two decades, various methods have been developed to study flood risk, including the analytical hierarchy process [10], fuzzy logic, genetic algorithm [11,12], variable fuzzy theory [13], hydrological forecasting system [14,15], decision tree model, multivariate statistics [16] and machine learning approaches [17]. The analytical hierarchy process model and geospatial techniques are the simplest ways to identify flood risk locations by assessing different influencing factors. However, inaccurate weights can result in arbitrary spatial distributions of flood risk potentials.

Therefore, the main objectives of this study were:

- To prepare an estimate of the flood hydrograph for the 2-, 5-, 10-, 25-, 50-, 100- and 500-year, 24 h storm for Petra catchment area.
- To develop a hydrological map of current flood risk, potential impacts of flash floods and floodplain zone maps.
- To delineate the inundation areas at different degrees of flood hazards.

2. Materials and Methods

Study Area

The research area is located in the south of Jordan, some 200 km south of the capital Amman and 130 km north of the Gulf of Aqaba, where the area is including the cities of Wadi Musa and Petra (Figure 1). Nestled in the Sherah Mountains, these cities offer breathtaking views of Wadi Araba in the Jordan Rift Valley. Petra, an awe-inspiring ancient city partially camouflaged in the windy southern Jordanian landscape, is the region's centerpiece. It is considered one of the New Seven Wonders of the World and an invaluable UNESCO Heritage Site, giving the region its prominence. The Nabataeans, who were skilled in hydraulic engineering, the manufacturing of iron and the refinement of copper, built the magnificent sandstone city in the third century BC. They used the soft stone cliffs to carve out palaces, temples, tombs, storerooms and stables. The Nabataeans benefited financially from the taxes collected from caravans travelling through their country since Petra served as an important hub for trade between Damascus and Arabia. Petra, known for its beauty and tranquility, is known as the "rose rock city" due to its red-hued sandstone structures. There are 39,400 people living in Wadi Musa and Petra cities, which are both located in the Petra District of the Ma'an governorate [18]. This area is well known for its abundance of dining establishments and lodging options, and it also acts as the main entry point to the Ancient City of Petra. The study region also includes the Al-Hussein Bin Talal University campus of the College of Archaeology, Tourism, and Hotel Management, which contributes significantly to the Jordanian economy by creating billions of dollars in income and thousands of jobs each year.

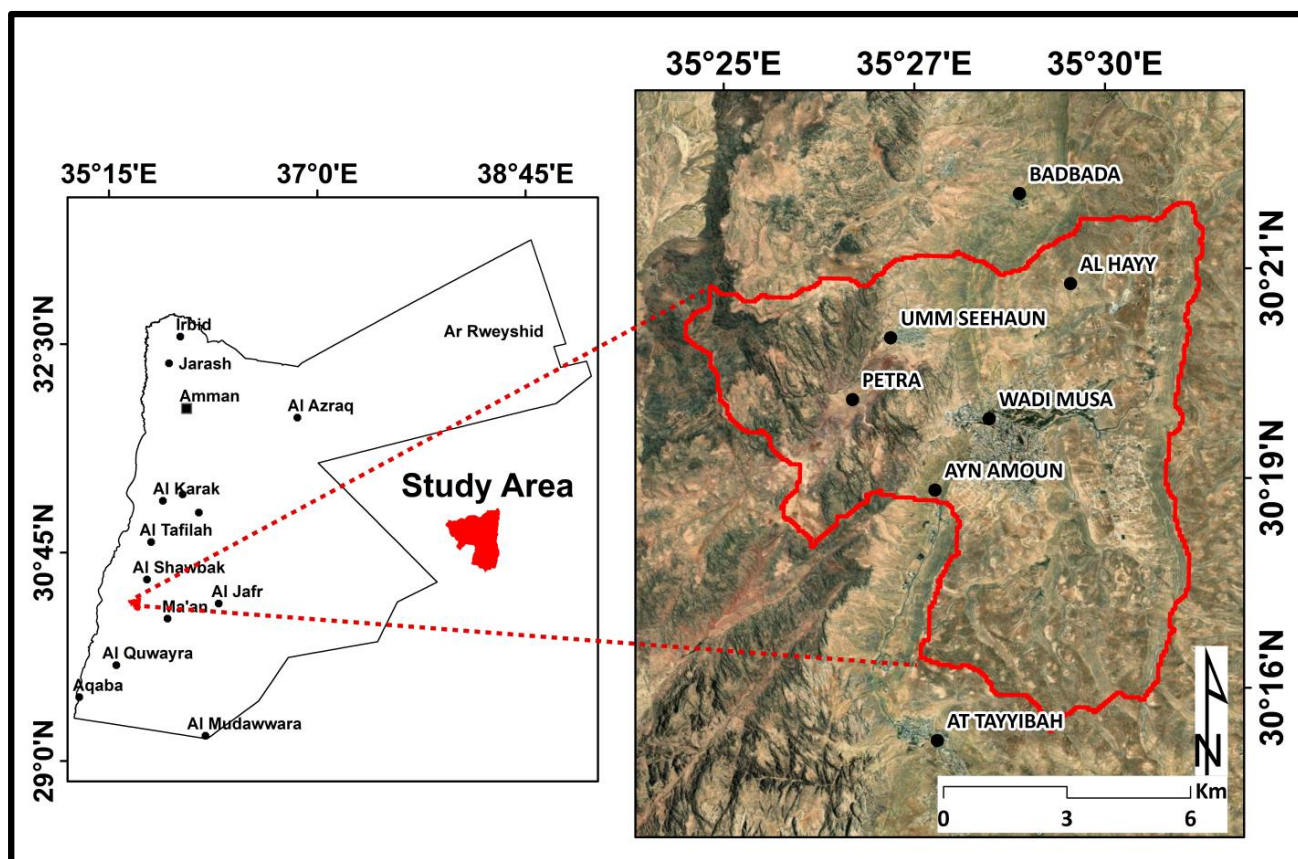


Figure 1. Location map of the study area.

3. Climate

The study area is situated in a region with a Mediterranean climate, characterized by aridity, cold winter precipitation and extremely hot, dry summers. Rainfall amounts are influenced by elevation above sea level and distance from the main mountain range. Most of the rainfall, which is predominantly orographic in origin, occurs between November and April. Table 2 presents the long-term rainfall parameters for the Wadi Musa Station. Historical data of the Wadi Musa watershed show that the long-term average rainfall is approximately 171 mm. Orographic rainfall prevails in the highland part of the study area. The heaviest 24 h rainfall is typically recorded between December and March, with no significant rainfall expected in October and May. On average, there are 35 rainy days per year, which can reach or exceed 60 days in particularly wet years.

Table 2. Long-term rainfall data for the Wadi Musa Station [19].

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Yearly
Maximum Rainfall Amount in 24 h (mm)	69	35	65	32	7.5	0	0	0	0	32	23	51	69
Mean No. of Rainy Days (Rainfall $\geq$ 0.1 mm)	4.4	4.7	3.8	1.1	0.3	0	0	0	0	0.6	1.8	3.7	20.4
Mean No. of Days with Precipitation $\geq$ 1.0 mm	4.5	4.9	3.8	1.1	0.2	0	0	0	0.1	0.9	2	3.8	21.3
Mean No. of Days With Rainfall $\geq$ 10.0 mm	1.7	1.5	1.1	0.4	0	0	0	0	0	0.3	0.4	1.3	6.7
Mean No. of Snowy Days	0.9	0.7	0	0	0	0	0	0	0	0	0	0	1.6

Maximum temperatures in the region can reach 42 °C in the summer and dip just below 0 °C in the winter. The daily average evaporation rate is about 6.8 mm, with breezes from the west and southwest being the predominant directions. The highest daily evaporation rate ever observed was 9.8 mm in June, and the lowest was 3.6 mm in December. Although lengthier and less intense rains connected to frontal troughs are

frequent in rainy years, this region is known for its brief, powerful downpours. Winter brings snowfalls to high altitudes, with an average of 5 days of snowstorm per year at Wadi Musa station. Altitude and distance from the mountain range affect temperature, with summer maximum temperatures on the highlands often recorded in July and averaging 26.8 °C. Winter temperatures for this climatic type vary from 5 °C to 6 °C, while absolute maxima are in the range from 37 °C to 39 °C.

4. Geology and Soil

The study area primarily consists of Upper Cretaceous and Paleogene strata (Figure 2a). The oldest rocks are the Finan Granitic from the Aqaba Complex, known for their distinctive red color. These are overlain by Cambrian and Ordovician sandstones, which are mainly subarkosic quartzose sandstones in shades of yellowish-brown, brown, pink and white. The Upper Cretaceous deposits are predominantly composed of limestone, including Nummulitic limestone, sandy limestone and dolomitic limestone, along with phosphorite, clay and marl. These layers extend to the Paleozoic and Lower Cretaceous sandstones in the west and form a broad connection that descends beneath the Quaternary sediments, creating a chain of mountains [20].

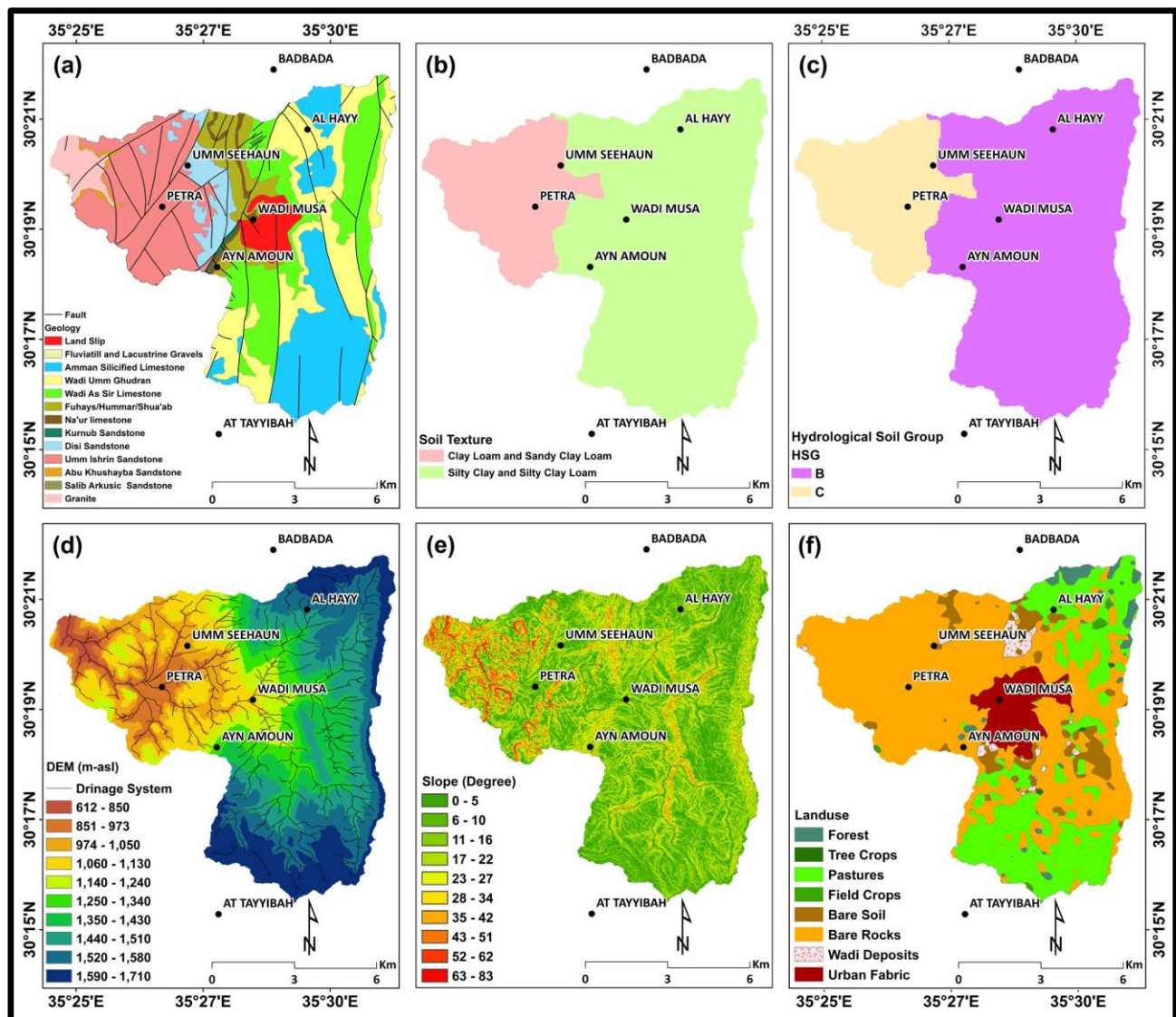


Figure 2. (a). Geological map, (b). soil texture, (c). soil hydrological group, (d). DEM (e). slope and (f). land use.

The soil type in the study area significantly influences flood susceptibility due to its impact on water infiltration and runoff. Soil texture affects porosity and permeability, with more permeable soils reducing flooding, while impermeable clay soils hinder infiltration and increase runoff [21]. Soil data for the research area were obtained from the level one-soil maps by the Ministry of Agriculture of Jordan [22]. The study area features four types of soil: clay loam, silty clay loam and sandy loam, with brown and yellowish-brown colors. According to the US Soil Conservation Service [23], all soil types exhibit low permeability and a relatively smooth structure (Figure 2b). The final soil map based on Hydrological Soil Groups (HSG) is shown in Figure 2c.

5. Topography and Slope

The Digital Elevation Model (DEM) with a high resolution of 12.5 m $\times$ 12.5 m, which is available from Shuttle Radar Topographic Mission (SRTM) dataset, was used to determine the drainage of the study area as presented in Figure 2d. It completely covers the area of the different villages and cities as Wadi Musa, Petra, Ayn Amoun, Al Hayy and Umm Seehaun. The elevation ranges from around 600 m above sea level (ASL) in the northwest to about 1700 m (ASL) in the south and north of the eastern area. Slope directly impacts the runoff and plays an important factor in triggering floods and influencing the grounds stability (Islam, et al., 2022 [24]). Slope ranges from 0 to 83°, and this makes the topographic relief becomes steeper with the direction of the flows westward in the lower part of the study area (Figure 2e). Because of the high difference in the elevation, especially in the lower parts of the basin, erosion features caused by rainfall and flashy floods have formed a scarp and steep canyon down adjacent to the confluence of the main tributaries (Wadi Al Moghare and Wadi Khaleel confluence), as can be seen in Figure 2d.

6. Land Use and Land Cover

The study area's land use and land cover (LULC) map were created using a Landsat 9 satellite image. The image was obtained from the Earth Resources Observation and Science (EROS) Center through the United State Geological Survey (USGS) Global Visualization Viewer [25]. Path 174 and row 39 were selected to cover the target area, and the specification of image is shown in Table 3. Cloud-free images were acquired for the summer season of 2022, and then the Landsat was georeferenced to the World Geodetic System 1984 (WGS84) datum and Universal Transverse Mercator Zone 36 North (UTM-36N) coordinate system. Intensive pre-processing, such as layer stacking, geo-referencing and image enhancement, was carried out to ortho-rectify the satellite image. The image was then processed in ENVI 5.3 software. Afterward, the image for the study area were extracted by clipping the study area using ArcGIS software.

Table 3. Specification of the 9 Operational Land Imager 2 (OLI-2) sensor used for classification.

Satellite	Date of Acquisition	Bands/Color	Grid Cell Size (m)
Landsat 9 OLI2	27 June 2022	Visible/NIR/SWIR	30

The on-screen digitizing method was used to sketch the main features from Landsat 9. The area was classified into these main classes: pastures, field crop, tree crops, bare rocks, bare soil, Wadi deposits and urban fabric, as displayed in Figure 2f. The Middle East's vegetation regions classify the study area as part of the Mediterranean region, according to [26,27]. The majority of the study area is covered by bare rocks, accounting for approximately 57.68%, while pastures cover 25.39%; forests, 2.18%; bare soil, 5.6%; urban areas, 6.8%; and the remaining area is covered by tree crops and Wadi deposits, totaling 1.97%. Urban areas with high population densities are concentrated in the middle of the study area, particularly in Wadi Musa and Petra, while the rest of the area has a low population density.

7. Methodology and Data Processing

In order to create a flood hazard map for the Petra area, various steps and data acquisition methods were undertaken as illustrated in Figure 3 of the methodology flow chart. The first step involved the use of different datasets, such as topographic, geologic, soil, digital elevation model (DEM) data with a spatial resolution of $12.5\text{ m} \times 12.5\text{ m}$ and satellite images to extract the LULC map. Additionally, all historical meteorological data, such as rainfall and runoff, were also considered. The second step was to create different thematic maps, including geologic, soil and LULC maps. These maps were created by reclassifying the original data sets and using ArcGIS software to visualize and analyze them, while the third step was to calculate the slope and aspect maps from the DEM data to evaluate the topography of the study area. These maps were then used to identify areas with high slope and to calculate the flow accumulation and drainage patterns of the area. The fourth step was to determine the flood-prone areas using the flood hazard analysis method. This involved overlaying the thematic maps created in the second step and identifying areas that are susceptible to flooding based on various factors such as soil permeability, LULC and topography. The fifth step was to validate the flood hazard map using historical flood data and field surveys. The final step was to generate the flood hazard map for the Petra area by integrating all of the above steps and presenting the results in a visually understandable manner.

Figure 3 illustrates the five essential steps used to accomplish the study's objectives. The hydrometeorological data were examined to determine the likelihood of the maximum rainfall intensities for various return periods. In the next step, the study delineated the boundaries of the drainage basins and computed their hydrological characteristics using both ArcGIS and WMS software packages. After that, the HEC-HMS 4.12 modeling was executed to model the rainfall/runoff relation and estimate the hydrologic inflow volumes and peak discharge values for each sub-basin for different return periods (2, 5, 10, 25, 50, 100 and 1000 years). The penultimate step focused on simulating the behavior of drainage in a watershed area using a hydraulic model (HEC-RAS). The final step was to evaluate the risk of floods on different land uses based on flood inundation maps in various return periods. In the end, the final flood risk map was produced by combining the hazard and vulnerability maps using the analytical hierarchy process (AHP) method, which is a multi-criteria decision-making tool that permits the integration of multiple factors into a single map. The study gave a higher weight to the hazard map than the vulnerability map, as the severity of the hazard is the primary determinant of flood risk. The last step of the methodology involved using the AHP to generate the flood risk map by summing the two composite index maps for hazard and vulnerability. The intermediate map of hazards was constructed using six weighted maps with the assistance of ArcGIS, while the intermediate map of vulnerability was generated by combining three weighted vulnerability indicator maps. This approach enabled the study to consider the various factors that contribute to flood risk and provided a comprehensive map of the level of risk in the study area.

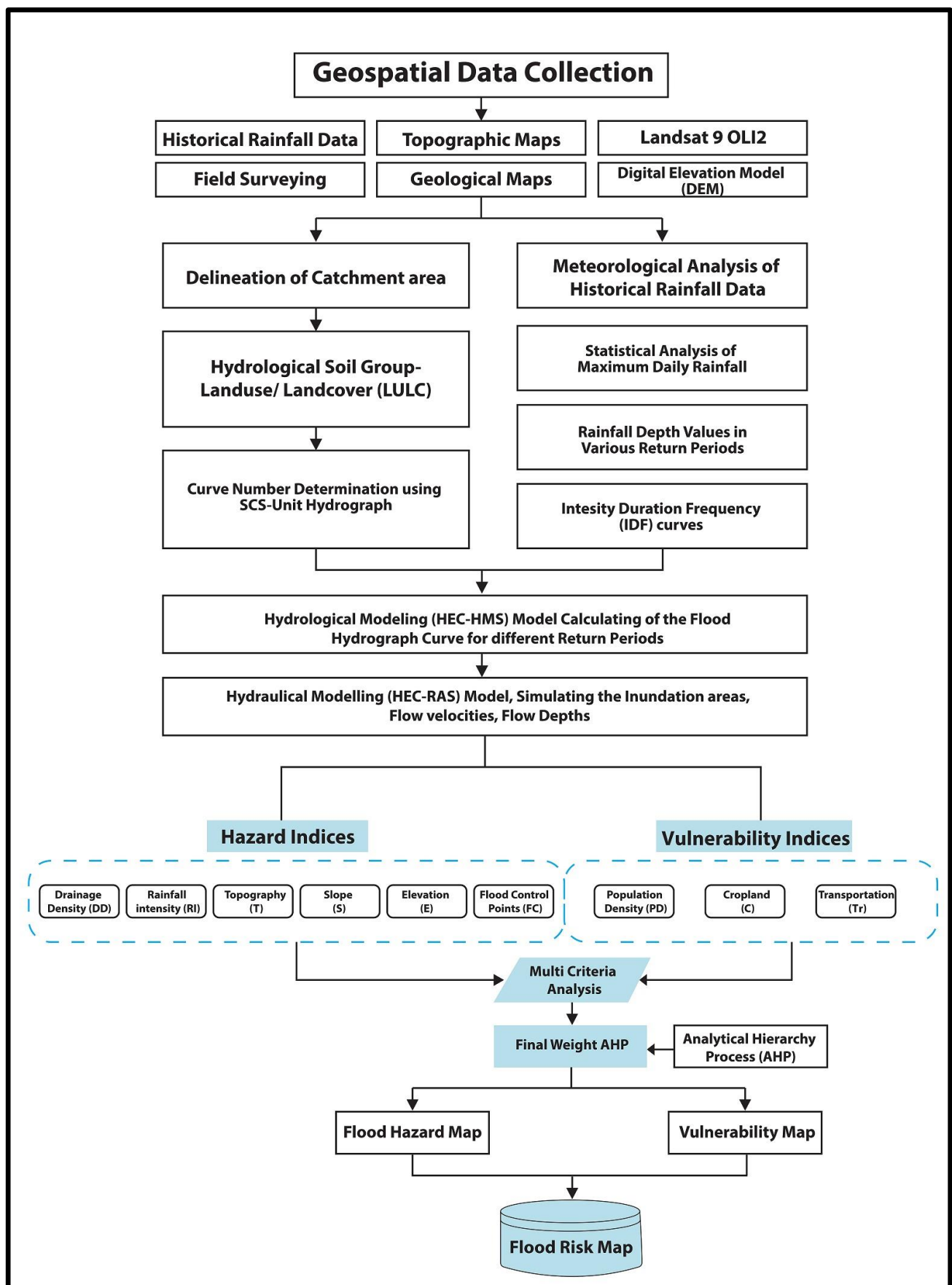


Figure 3. Flowchart showing the methodology for this study.

8. Catchment Delineation and Their Characteristics

The catchment areas were delineated using a high-resolution 5 m Digital Elevation Model (DEM) obtained from WMS software. The study area was divided into four sub-catchments (A, B, C and D), as shown in Figure 4. The morphometric parameters of these sub-catchments are detailed in Table 4. Basin curve numbers were calculated using the WMS software using the GIS attribute calculator tool, which incorporated soil and land use/land cover layers.

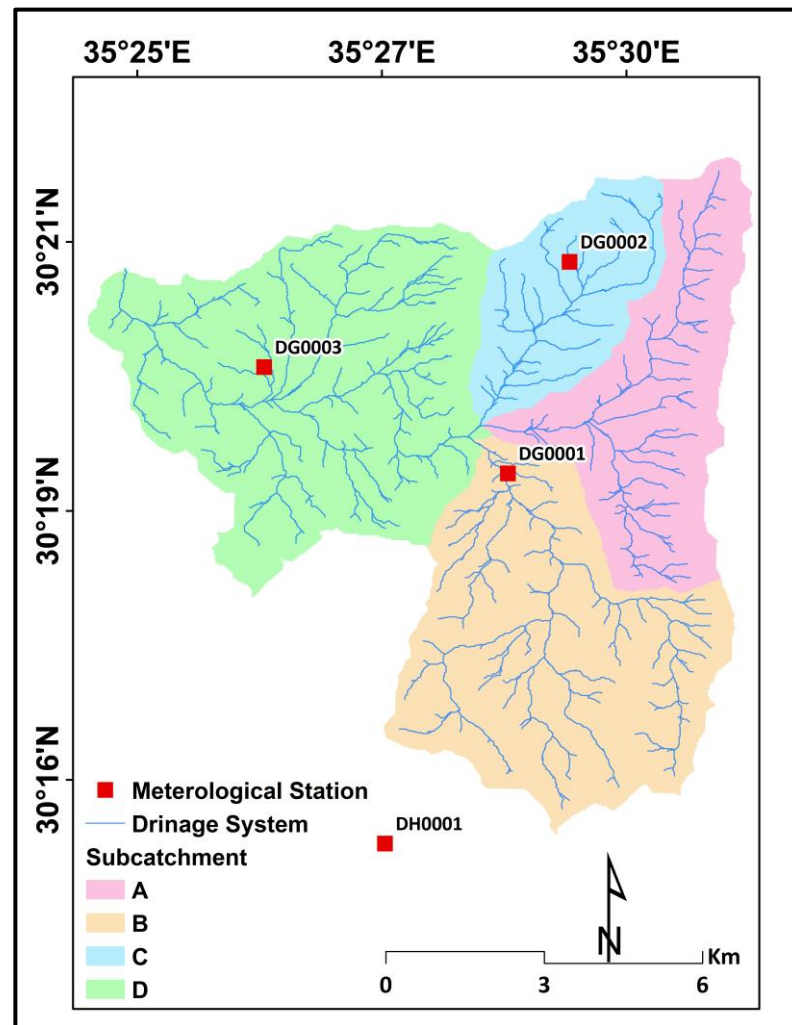


Figure 4. Sub-catchments of the study area.

Table 4. Morphometric characteristics of the sub-catchments.

Sub-Catchment	Sub-Catchment Area km ²	Sub-Catchment Slope (BS) (m/m)	Basin Length (m)	Basin Curve Number (CN)	Max. Flow Slope (MFS) (m/m)	Max. Flow Distance (MFD) (m)	Max Stream Length (MSL) m	Max Stream Slope (MSS) m/m
A	15.45	0.2241	6544.77	87.5	0.0662	7193.11	8110.45	0.0621
B	25.32	0.2154	7538.06	86.9	0.0595	10,114.61	9742.15	0.0584
C	9.5	0.2241	5509.12	86.2	0.0836	7193.11	6783.78	0.0831
D	28.76	0.3896	7307.12	94.7	0.0862	10,895.56	10,205.04	0.0755

9. Analysis of Rainfall Data

The daily rainfall data from 1960 to 2020 were collected from database of the Ministry of Water and Irrigation for the four rainfall gauge stations located in the catchment area, as shown in Figure 5. The purpose of this data collection was to analyze the rainfall, including the amount of daily rainfall and to estimate the maximum precipitation quantities, frequency and distribution. To precisely estimate the magnitude of flash floods and their anticipated frequency, this analysis was required.

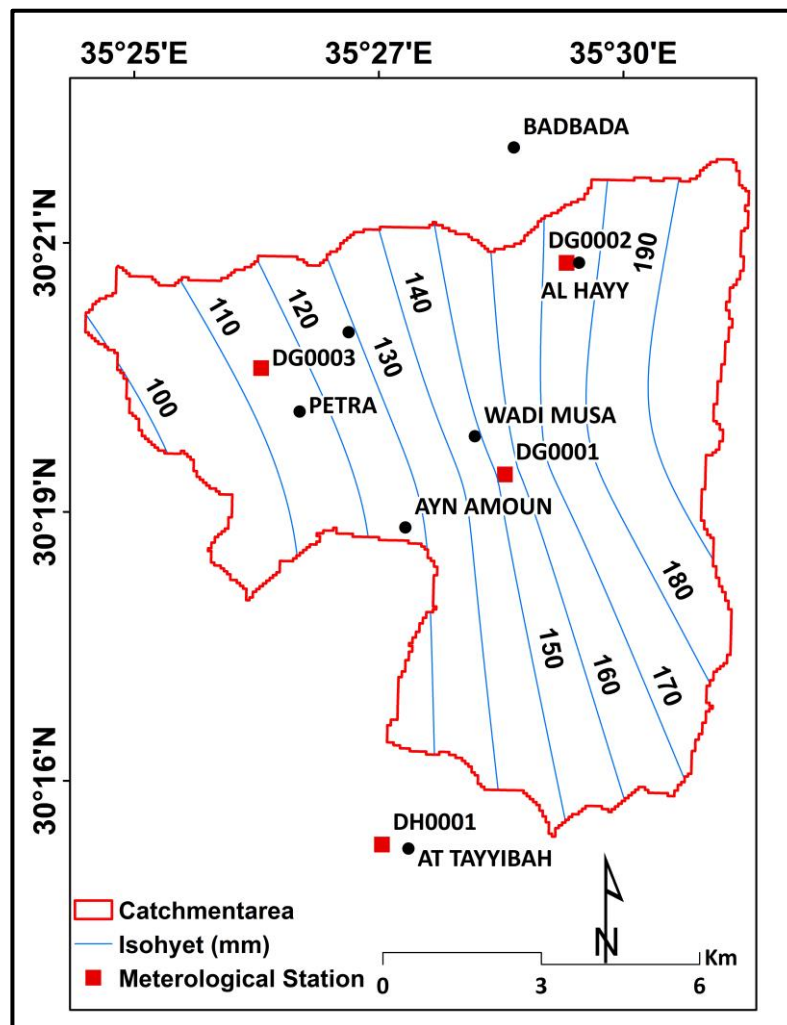


Figure 5. Annual rainfall (mm) with the gauge stations.

In the highland portion of the catchment region, orographic precipitation is the dominant kind of precipitation, with the largest amounts reported over 24 h between December and March. Significant precipitation is not anticipated between October and May. On the other hand, rainfall in the study area is characterized by being sparse and varying on a daily, monthly and annual basis. This is a result of the significant heterogeneity and disparity in the spatial and temporal distribution of rainfall over the catchment area, which reflected the hydrological features of the local environment. After extended droughts, another characteristic of rainfall is that it frequently comes in the form of very intense showers, which greatly erodes agricultural land and washes debris away. In years with heavy precipitation, the average number of wet days' rises to or exceeds 60. The annual average rainfall for all rainfall stations was used to compute the areal distribution of rainfall over the catchment areas, and the results are given in Figure 5. The eastern highlands of the catchment region experienced the highest rainfall levels, which declined toward the

western part with an average yearly precipitation of less than 100 mm. Between 1960 and 1992, there was an observed increasing tendency, and from there, a decreasing trend started (Figure 6).

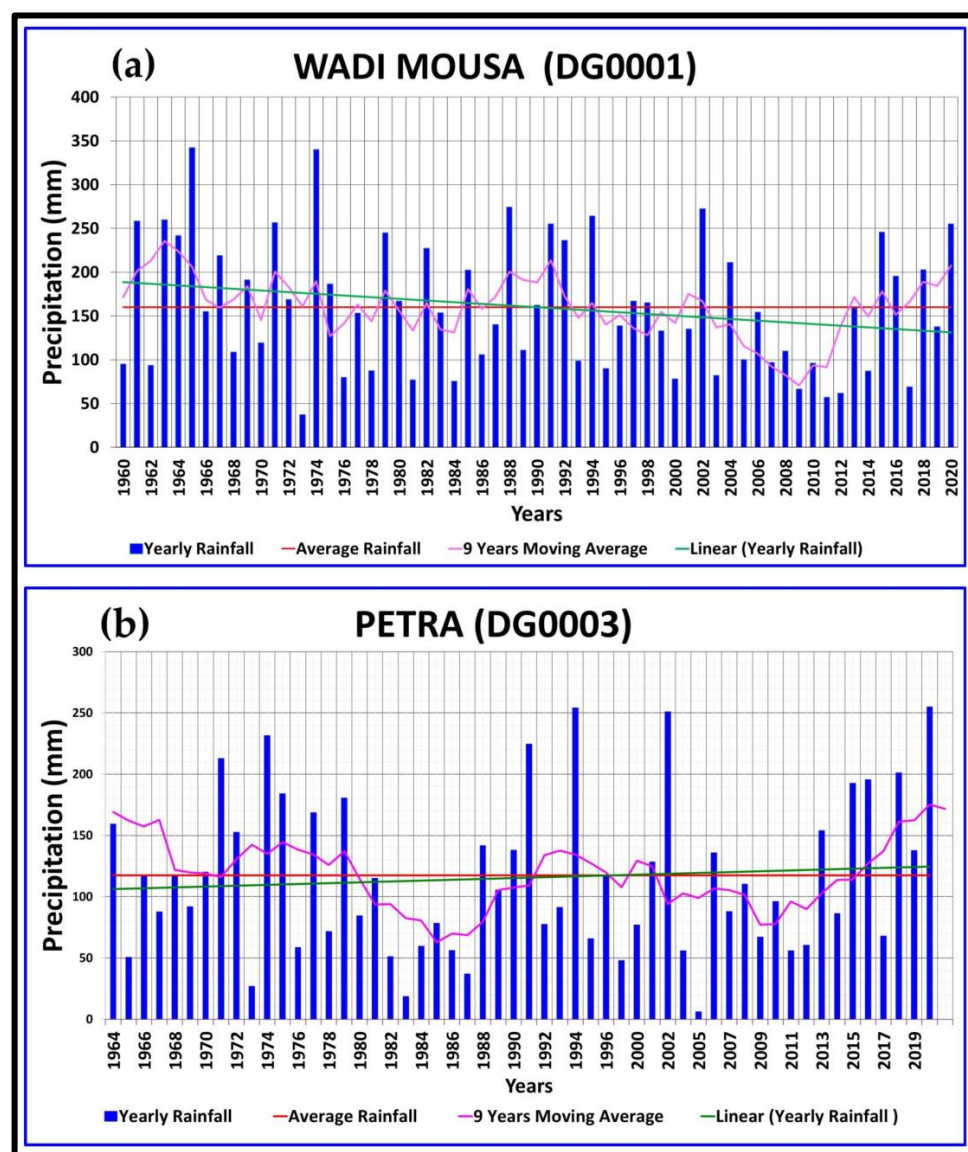


Figure 6. Long-term annual rainfall of (a) Wadi Musa and (b) Petra rainfall gauging stations with a nine-year moving average.

In addition, the moving average, which is a statistical method, is used to smooth out short-term fluctuations and highlight long-term trends in data by averaging a set number of consecutive periods, which shifts forward over time. In rainfall analysis, moving averages help identify underlying trends, detect anomalies, and forecast future rainfall patterns. This technique involves collecting historical rainfall data, choosing an appropriate window size (e.g., days, months) and calculating the average for each period. Each station in the study area was subjected to 3-, 5-, 7-, 9- and 11-year moving average calculations. In order to preserve the effects of lengthier wet and dry cycles in the records of long-term yearly rainfall, the random component is dampened and smoothed down using the nine-years moving average trend type (Figure 6). By contrasting the nine-year moving average line with the catchment area's average yearly rainfall, the rainy period may be identified. Around the long-term mean, this line varied. The nine-year moving average line, however, was situated above the long-term average line during the rainy period and below it during

the drought period. The moving average's trend line displayed a steadily declining value over time.

The rainfall Intensity-Duration-Frequency (IDF) curves indicate the likelihood that specific rainfall intensity, duration and return period will occur with comparable features in a graphical format. It is employed to establish the frequency of a specific precipitation in terms of the length and severity of the event [28]. For all gauge stations inside and outside the catchment area, the daily rainfall depth and maximum records of rainfall stations are accessible for 80 years (1960–2020). Thus, for all rainfall stations, IDF computations and IDF curves were created (Figure 7). The data on rainfall have been used to estimate the amount of rain and the projected intensity for a range of return intervals (2, 5, 10, 25, 50, 100 and 1000 years).

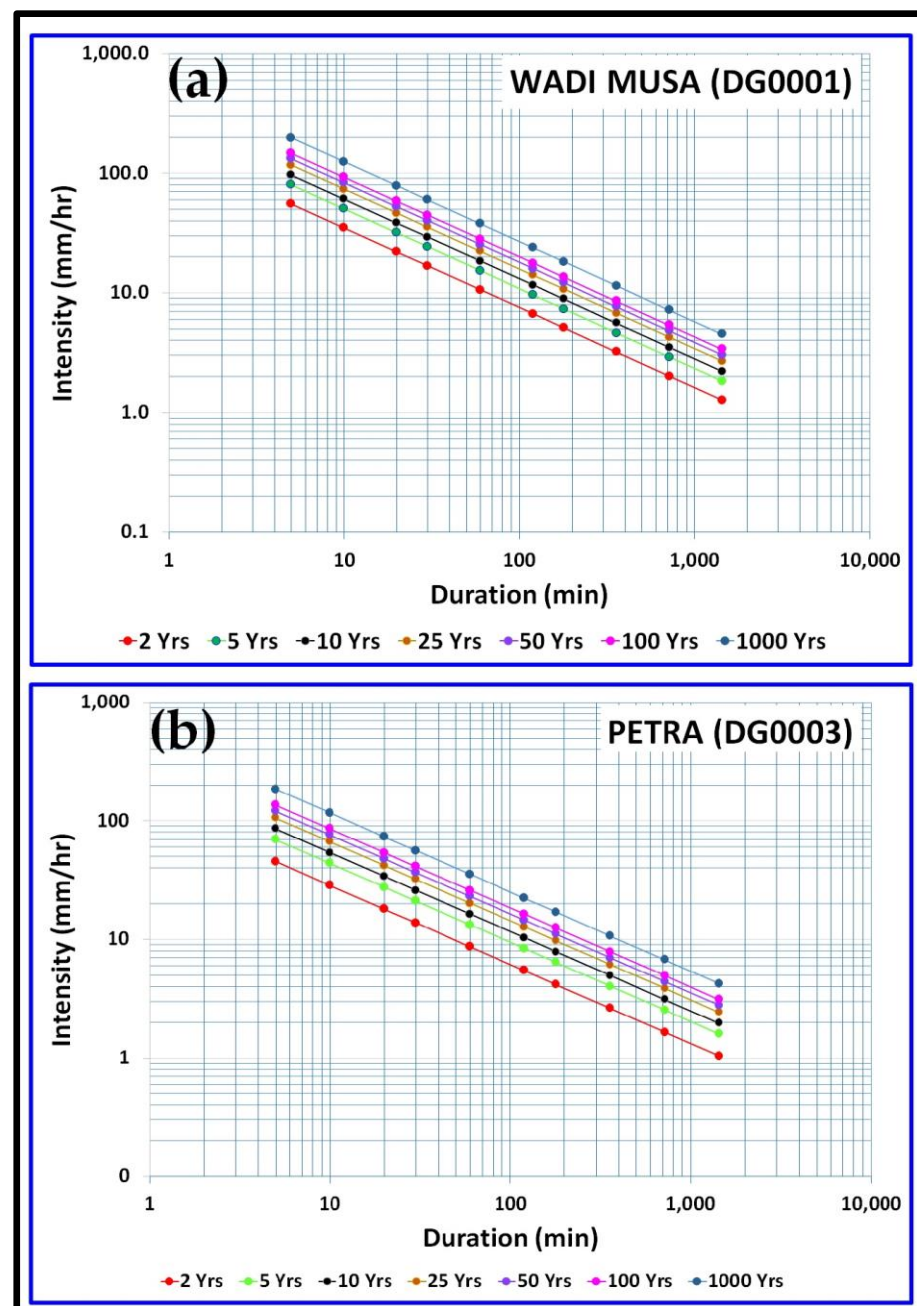


Figure 7. IDF curves: (a) Wadi Musa and (b) Petra rain gauging stations.

The daily rainfall depth and maximum records from rainfall stations, covering the years 1960–2020, are available for gauge stations both inside and outside the catchment area. Consequently, IDF computations and IDF curves were prepared for all rainfall stations (Figure 7). The rainfall data were used to estimate the depth and expected intensity of rainfall during various return periods (2, 5, 10, 25, 50, 100 and 1000 years). Figure 7 illustrates the rainfall intensity for these different return periods, ranging from 25 mm to approximately 102 mm at Petra station, while the Wadi Musa station showed an increase from 31 mm to 109 mm. This high intensity is responsible for the flash floods occurring in the catchment area.

10. Hydrological Analysis

The hydrological study was performed using the HEC-HMS model to determine the features of the hydrological drainage basin and to create the necessary hydrograph curves for the Petra catchment based on the synthetic unit hydrograph of the Soil Conservation Service (SCS-UH). In order to estimate rainfall losses and peak discharge through the relationship between runoff behavior and total rainfall [29,30], which is required to calculate the surface runoff in the watershed drainage basins, it was necessary to use the basic formulas of the SCS-CN model of runoff for the Petra catchment area. According to calculations, Petra's catchment area's curve number was 86.63 (Table 5 and Figure 8).

The maximum flash flood inflow or peak discharge (m^3/s) of the Petra catchment was calculated for different return periods as presented in Figure 9 and Table 6.

The discharge volumes for various return periods were calculated and are presented in Table 7. The analysis indicates that the highest discharge volumes occur during the 1000-year return period with a 24 h duration, reaching approximately 5 million cubic meters (MCM). Notably, the area experienced a significant flood event in 2018. During this event, the peak flood discharge reached 292 (m^3/s), with a maximum volume of 3.15 MCM being discharged towards Wadi Araba from the catchment area.

Table 5. Calculated CN for the Petra catchment area.

HSG	Land Use Description	CN	Area km^2	$\text{CN} \times \text{A}$
C	Bare Rocks	95	18.429	1750.746
C	Wadi Deposits	89	0.024	2.160
C	Bare Soil	91	0.158	14.353
C	Field Crops	88	0.024	2.135
B	Bare Rocks	95	27.055	2570.246
B	Bare Soil	86	4.271	367.272
B	Wadi Deposits	85	1.395	118.594
B	Pastures	79	20.249	1599.667
B	Forest	66	1.456	96.089
B	Urban Fabric	98	5.569	545.739
B	Field Crops	81	0.413	33.413
Average CN = 86.63				

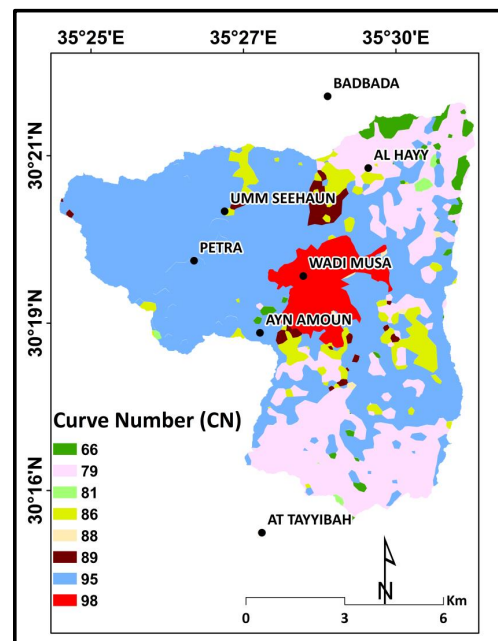


Figure 8. CN distribution value for the Petra catchment.

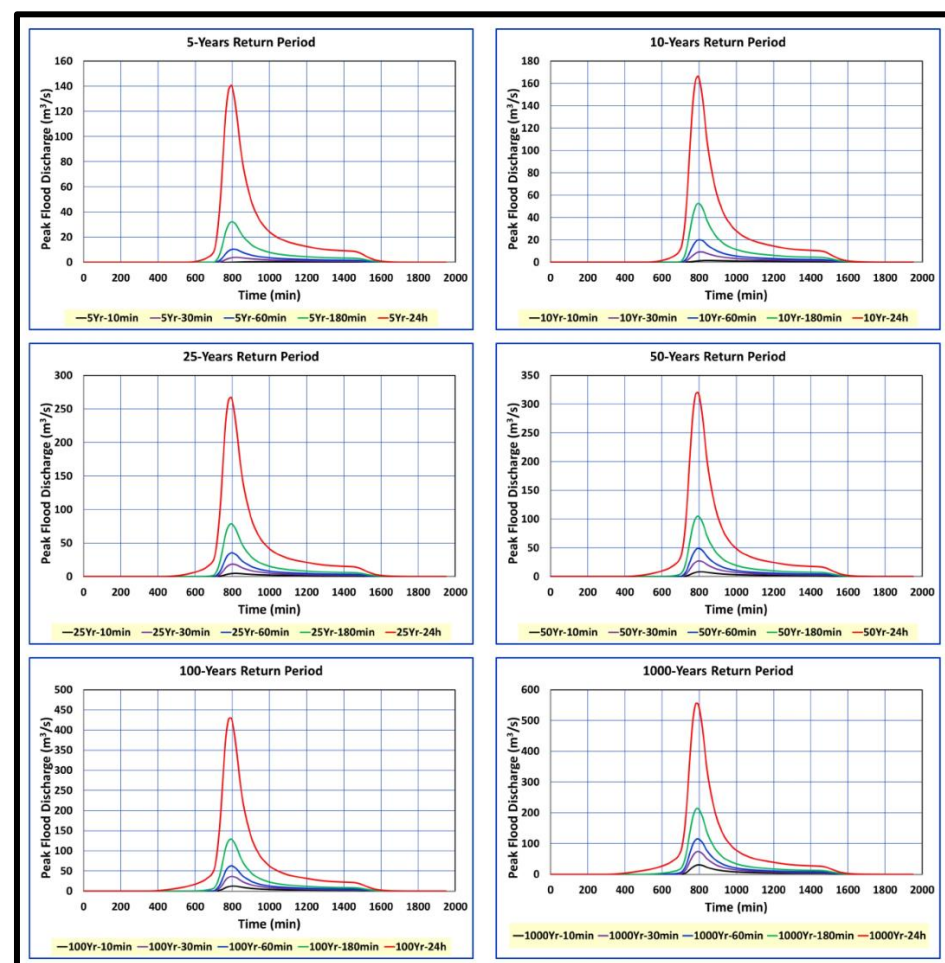


Figure 9. The flood inflow hydrographs of the Petra catchment outlet created by HEC-1 for the different return periods (5, 10, 25, 50, 100 and 1000 years) with rainfall intensities of 10, 30, 60 and 180 min and 24 h.

Table 6. The peak discharge (m^3/s) at different durations and return periods.

Time	Storm Return Periods and Peak Flows					
	5 Years	10 Years	25 Years	50 Years	100 Years	1000 Years
10 min	0.407	1.53	4.67	8.16	12.37	30.74
30 min	3.9	9.18	18.48	27.07	36.7	73.77
1 h	10.36	20.01	35.62	48.92	63.23	115.51
3 h	32.28	52.7	78.94	105.07	129.15	213.3
24 h	140.69	166.23	266.61	319.74	428.42	553.14

Table 7. The volumes (million cubic meter (MCM)) at different durations and return periods.

Time	Storm Return Periods and Volumes					
	5 Years	10 Years	25 Years	50 Years	100 Years	1000 Years
10 min	14,691.6	41,989.5	94,257	142,974	198,418.5	418,541.4
30 min	82,455.3	156,654.4	275,016.6	376,238.7	486,549.9	902,259
1 h	172,219.5	293,292.9	474,255	624,314.7	784,572.3	1,369,326.6
3 h	436,208.4	666,694.8	959,994.9	1,252,279.8	1,522,422	2,475,441
24 h	1,652,352.3	1,940,679.9	3,086,547.3	3,701,084.4	4,973,926.5	6,452,630.1

11. Hydraulic Model (HEC-RAS)

Channel and floodplain geometry, as well as Manning's roughness values, are needed by the hydraulic model (HEC-RAS 6.5). WMS and HEC-HMS software's were used in this study to create the input data for HEC-RAS. The channel network structure was modeled by HEC-RAS as a collection of linked reaches. Stream centerline, main channel banks and cross-section cutlines are the three basic geometry data needed for HEC-RAS. From the DEM in the catchment area, seven main channels that were split into eight reaches with clearly defined junctions were extracted. As seen in Figure 10, cross sections were manually created perpendicular to channel flow lines. Networks and cross-sectional profiles for the seven channels were transferred from WMS into HEC-RAS. With accurate channel networks, the HEC-RAS model was run. It performs interpolations along the reaches and computes the depths based on the peak discharge estimated by HEC-HMS at the identified cross sections [31]. The HEC-HMS was used to determine the peak discharge data for each watershed, and the HEC-RAS was then utilized to estimate the water depths along the flood course. WMS imported all return period data and calculated it. The flood path in HEC-RAS was established using around 100 cross-sections taken from the Triangulated Irregular Network (TIN) of the study region. The original model has one profile every 250 m on average. The collected profiles were interpolated to construct cross profiles in order to have an even finer spatial step. A profile was added as soon as the distance between two profiles surpassed 200 m, defining the flood path across 5–8 cross sections in each channel. To calculate and simulate the water surface elevations, flow velocities, flow depths and spread of the flash flood occurrences based on the conventional step technique, this model used the Manning empirical formula [32]. The roughness coefficients (Manning n -values) were assigned to each cross-section. Aerial photos of the Wadis were used to assign coefficients, which were then confirmed or corrected by field observations and nearly determined based on the field visits. The study area followed the USGS Guide for Choosing Manning Roughness Coefficients (Manning's n) for Natural and Flood Plain [23]. Manning's n roughness coefficients were 0.03 for river area, 0.10 for agriculture area, 0.08 for urbanized area and 0.04 for bare soil in the research area. Additionally, the flow regime in HEC-RAS was set to be mixed, and the normal depth was the slope of the channel segment [33,34]. The condition for the upstream and downstream boundaries was set to a normal depth.

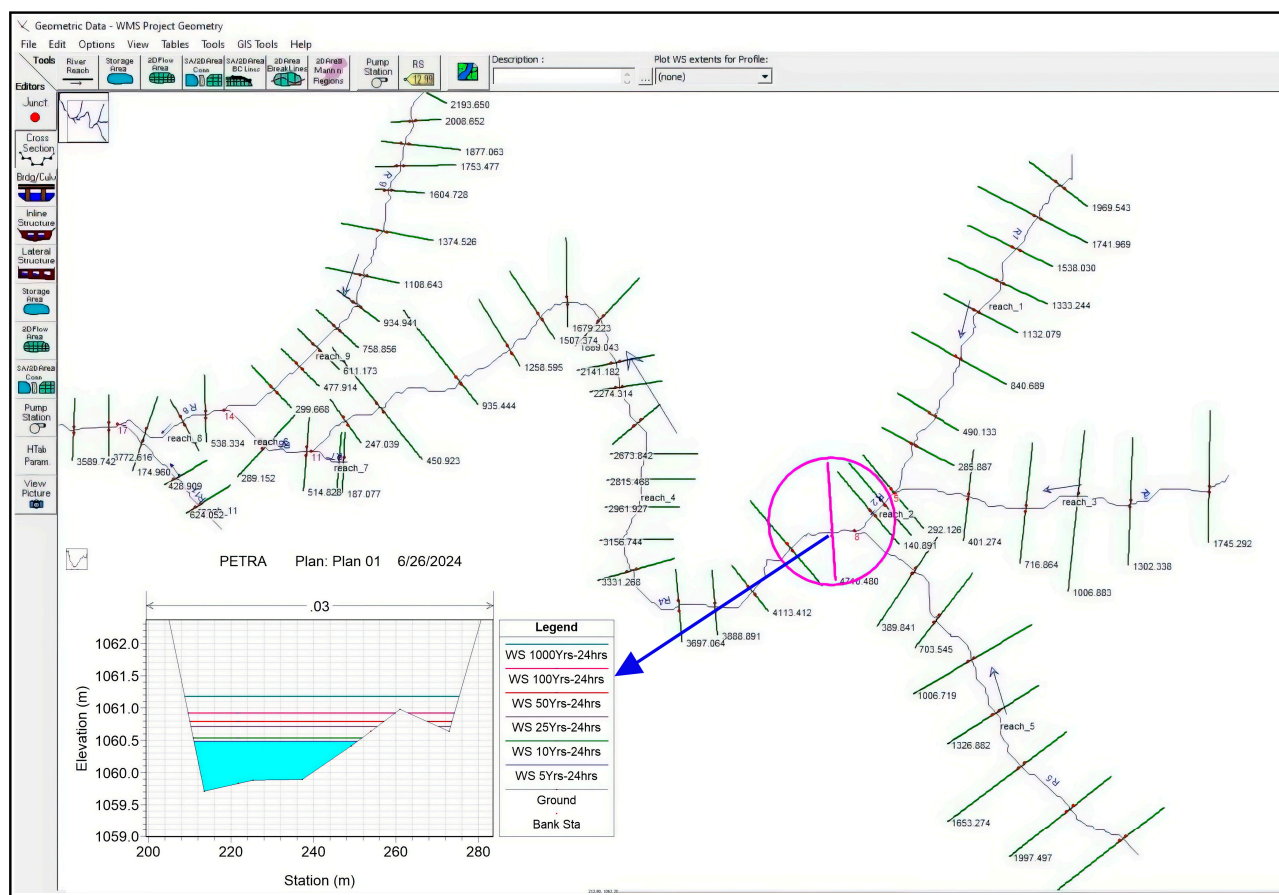


Figure 10. Perpendicular cross sections and water depth along the Wadi course.

12. Analytical Hierarchy Process (AHP)

Multi-criteria decision-making (MCDM) methods are essential for addressing complex decisions that involve multiple, often conflicting criteria. Among these methods, the AHP is particularly popular for its structured and systematic approach. AHP breaks down a decision problem into a hierarchy of simpler sub-problems, allowing each to be analyzed independently. This involves defining the problem, creating a hierarchy, performing pairwise comparisons, transforming subjective judgments into objective data. This method is highly effective in fields such as resource allocation, strategic planning, and risk management. AHP excels at quantifying the weights of various criteria through pairwise comparisons, offering a comprehensive and consistent decision-making framework. Its flexibility and robustness make AHP a preferred method across various disciplines, ensuring well-informed and balanced decision outcomes [1,35]. To analyze and forecast natural hazards, the AHP method has been widely employed [36–38]. The analytical hierarchy technique and the mathematical underpinnings of decision-making analyses were first put forth by Saaty [39,40]. He described the AHP as a mathematical approach for researching problems involving decision-making. The AHP technique transforms issues into weighted, quantifiable numerical relations. When mapping flood susceptibility, it is critical to pinpoint the factors that influence flooding so that GIS-based environmental data can be used for multi-criteria decision-making. The majority of the time, the identification of flood-causing elements is based on prior research or preferences developed through experience. The elements that influence flood susceptibility modeling vary by region and depend on the significance and impact of each individual factor. Therefore, many different controlling factors, including slope, elevation, land use, rainfall, and distance from the stream, among others, can be used for flood susceptibility analysis and modeling. A

review of pertinent research can be used to determine the independent flood impacting factors [41–44]. These criteria are ranked in order of relative relevance before their weights are determined. As shown in Table 8, the selected factors in this study were divided into hazard and vulnerability parameters. A pairwise comparison matrix was then built for each criterion to enable a significant comparison after all criteria have been sorted in a hierarchical order. The relative relevance between the criteria was rated from 1 to 9 (Table 9), with lower values denoting less importance and higher values denoting greater importance. Nine indices based on available data were developed after carefully examining the flash flood characteristics linked to risk and vulnerability in the study area and studying the literature's suggestions. Elevation (E), Landuse/Landcover LULC, Slope (S), Drainage density (DD), Flood Control Points (FCP) and Rainfall intensity (RI) make up the six risk indices, while Population Density (PD), Cropland (C) and Transportation (Tr) make up the three vulnerability indices.

Table 8. AHP hierarchy parameters for the Petra catchment area.

Flood Risk (FR)		
Hazard Indices (HI)		Vulnerability Indices (VI)
Conditions	Triggering	Social, Economic, Physical
Elevation (E)	Rainfall Intensities (RI)	Population Density (PD)
Land Use/Land Cover (LULC)		Cropland (CL)
Slope (S)		Transportation (Tr)
Drainage Density (DD)		
Flood Control Points (FCP)		

Table 9. Index comparison based on binary combination Reprinted/adapted with permission from Ref. [39].

Scale	Judgment of Preference	Description
1	Equal Importance	Two factors contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one over the other
5	Essential Importance	Experience and judgment strongly important favor one over the other
7	Very/strong Importance	Experience and judgment strongly important favor one over the other
9	Extreme Importance	The evidence favoring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate preference between adjacent scales	When compromise is needed
1/3, 1/5, 1/7, 1/9	Values of inverse comparison	When compromise is needed

In multi-criteria decision analysis, the selection of geographical reference elements or criteria is a crucial stage [45]. Pairwise comparisons are used in the AHP approach to assign a weight to each component or criterion based on how important they are. The weight of a component is determined by how influential it is [39,40]. Ayalew and Yamagishi [46] recommended that individual influencing factors be observable and pertinent for the full study region. The suggested methodology proposes a pairwise comparison with a matrix of 9 by 9 items with diagonal elements equal to 1. The AHP method's requirements for the Petra catchment region are arranged hierarchically in Table 10. The values in each row express the relative weights of each parameter. The importance of slope in relation to the other characteristics that are listed in the columns is demonstrated in the first row of the table. Saaty [39] provides more information on the application of the AHP.

Table 10. Parameters of flood hazard: analytical hierarchy process.

Parameters	RI	E	S	FC	DD	LU	CL	TR	P
RI	1	3	3	3	3	3	5	5	5
E	0.33	1	3	1	3	5	3	5	5
S	0.33	0.33	1	1	1	5	3	3	5
FC	0.33	1	1	1	1	3	3	3	3
DD	0.33	0.33	1	1	1	3	5	5	5
LU	0.33	0.20	0.20	0.33	0.33	1	1	1	1
CL	0.20	0.33	0.33	0.33	0.20	1	1	3	3
TR	0.20	0.20	0.33	0.33	0.20	1	0.33	1	1
P	0.20	0.20	0.20	0.33	0.20	1	0.33	1	1
Sum	3.27	6.60	10.07	8.33	9.93	23.00	21.67	27.00	29.00

Table 11 includes the normalized values of the parameters of Table 10, their mean and, eventually, the corresponding weight w of each factor.

Table 11. Normalized flood hazard parameters: analytical hierarchy process.

Parameters	RI	E	S	T	DD	LU	CL	TR	P	Mean	W_i
RI	0.31	0.45	0.30	0.36	0.30	0.13	0.23	0.19	0.17	0.27	2.71
E	0.10	0.15	0.30	0.12	0.30	0.22	0.14	0.19	0.17	0.19	1.89
S	0.10	0.05	0.10	0.12	0.10	0.22	0.14	0.11	0.17	0.12	1.18
T	0.10	0.15	0.10	0.12	0.10	0.13	0.14	0.11	0.10	0.12	1.16
DD	0.10	0.05	0.10	0.12	0.10	0.13	0.23	0.19	0.17	0.13	1.28
LU	0.10	0.03	0.02	0.04	0.03	0.04	0.05	0.04	0.03	0.04	0.40
CL	0.06	0.05	0.03	0.04	0.02	0.04	0.05	0.11	0.10	0.06	0.53
TR	0.06	0.03	0.03	0.04	0.02	0.04	0.02	0.04	0.03	0.04	0.33
P	0.06	0.03	0.02	0.04	0.02	0.04	0.02	0.04	0.03	0.03	0.31

It is necessary to assess the consistency of the AHP's eigen vector matrix after it has been created. The following index was used to assess the necessary level of consistency.

$$CR = \frac{CI}{RAI} \quad (1)$$

where

CR—consistency ratio, CI—consistency index and RAI—random index.

The values of the random index are given in Table 12. These numbers depend on how many criteria are used. The number of criteria in this study was nine, and as a result, the RID was 1.45. The consistency ratio (CR), according to AHP's idea, must be 0.1. Equation (1) was used to calculate CI, where n is the number of criteria, and λ_{max} is the comparison matrix's maximum eigenvalue. Specific tables provide RAI values [47,48].

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

Table 12. Random index (RAI) used to compute consistency ratios (CR) Reprinted/adapted with permission from Ref. [39].

N	1	2	3	4	5	6	7	8	9	10
Random Index (RAI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

For the values of Table 11, the CI was calculated for $\lambda_{max} = 9.74$, $n = 9$ and $RI = 1.45$. Eventually, the consistency ratio has been calculated $CR = 0.06$. Since CR 's value was lower than the threshold (0.1), the weights' consistency was confirmed.

According to the literature and the District Disaster System theory [49], the definition of hazards indicated by Equation (6) is the basis for the assessment of flood risk.

$$Risk = Hazard + Vulnerability \quad (3)$$

where the evaluation area's natural environment and hydro-climatic variables are described by the premise, Hazard. Socioeconomic conditions in the area are represented by vulnerability, which also indicates potential losses. Risk denotes the likelihood and potential loss depending on floods of various intensities. The conceptual model of regional flash flood risk assessment, according to Lin and Lee [49], can be stated as Equation (4).

$$R = (H, V) \quad (4)$$

where

$$H = (h) = \sum_{i=1}^n w_i h_i \quad (5)$$

$$V = (v) = \sum_{j=1}^n w_j v_j \quad (6)$$

$$R = (H, V) = \sum_{i=1}^n w_i h_i + \sum_{j=1}^n w_j v_j \quad (7)$$

where h_i and v_j stand for the values of the vulnerability and hazard indices following standardization treatments, respectively. The weights for the vulnerability and hazard indices are w_j and w_i , respectively.

A number of GIS layers were gathered and produced to complete this work. These layers included those for slope, drainage system, population, land use, rainfall, flood control and transportation. One or more "composite index map(s)" were made using these GIS layers after they were normalized, weighted, and categorized [50]. Each grid cell will have a score in the final composite index map(s), and that score will have a range depending on the weight given. The two composite index maps for hazard and vulnerability were added together to create the flood risk index map. Equation (5) was used to overlay the six additional intermediate weighted maps. Equation (6) was used to combine the three vulnerability elements to create the intermediate vulnerability map, as shown in Equation (7).

13. Results and Discussion

HEC-HMS software was used for hydrological modeling to provide peak discharges for six return periods. The goal was to perform rainfall-runoff modeling, with the resulting runoff hydrographs serving as key inputs for flood simulation. Simulations in HEC-RAS were conducted as steady-state analyses for 2-, 10-, 25-, 50-, 100- and 1000-year return periods, based on the hydrographs from HEC-HMS. The results were then processed by WMS after importing the peak discharges from HEC-HMS into HEC-RAS. Figure 11 illustrates how HEC-RAS interpolated the findings of the data on water-surface elevation to define the flood inundation. This calculation showed that the upstream, urbanized, middle area of Wadi Musa city, which is distinguished by low altitudes, is the area most affected by the flood. For a 1000-year flood, the water depth in this area can reach a maximum of 8 m. The width of the inundated areas attained during the 100-year flood and the 1000-year flood, respectively, was 130 m and 195 m. It is obvious that flood flooding will occur during the 100- and 1000-year rainfall return periods when the amount of the flooded water exceeds the Wadi bank.

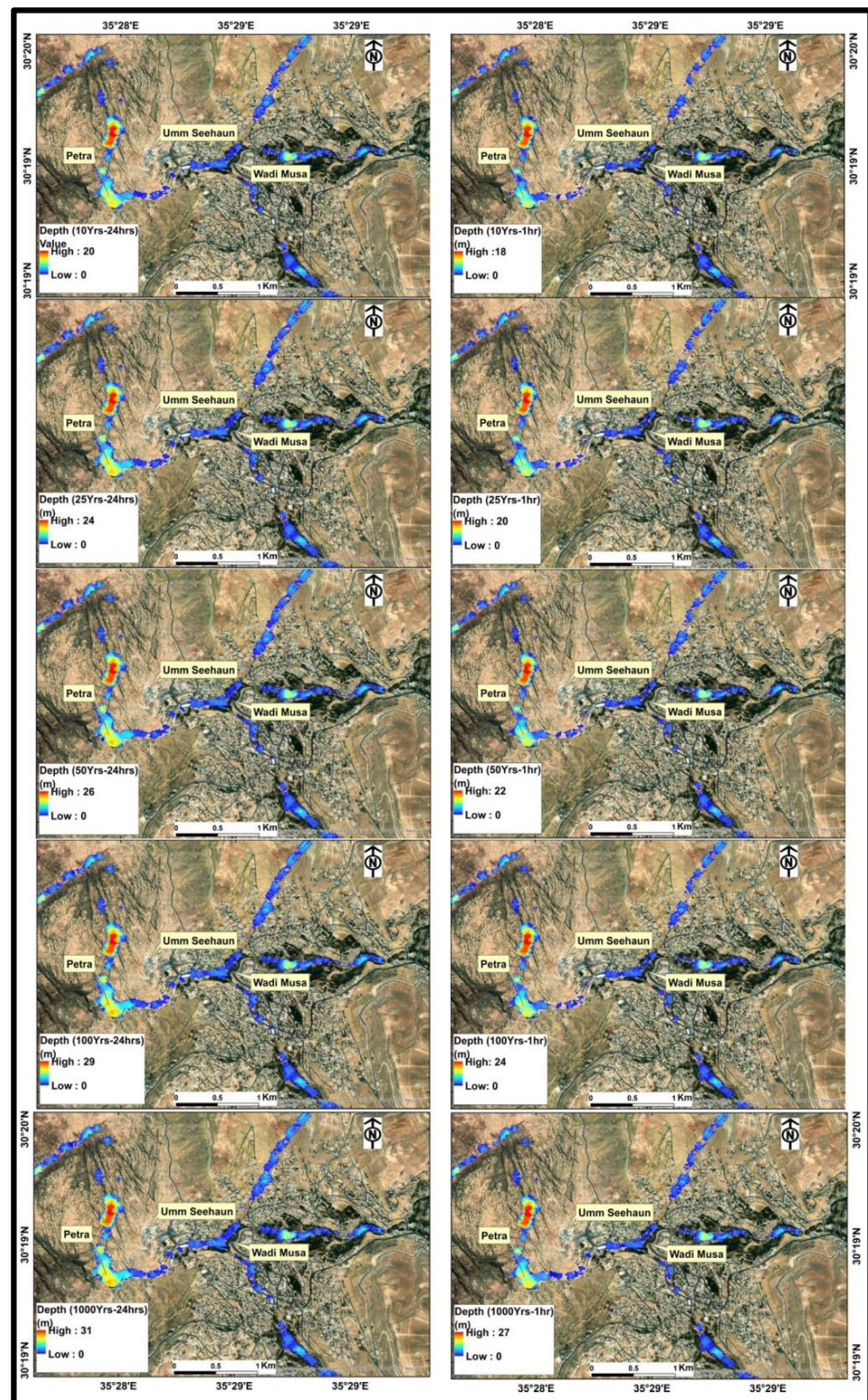


Figure 11. Flood inundation map with 1 and 24 h rainfall intensity for the return periods of 10, 25, 50, 100, and 1000 years.

13.1. Elevation (E) and Slope (S)

Water flows from higher to lower elevations and slopes, making these two parameters critical factors in flood hazards. Higher elevations typically have a lower flood risk, while lower, flat regions are more vulnerable. Elevations in the study area range from 612 to

1710 m above sea level, with slopes varying from 0 to 83 degrees, resulting in steeper topography and westward water flow in the lower half of the region; as a result, the topography relief in the lower half of the study region became steeper with the direction of the flows westward (Figure 12b,c).

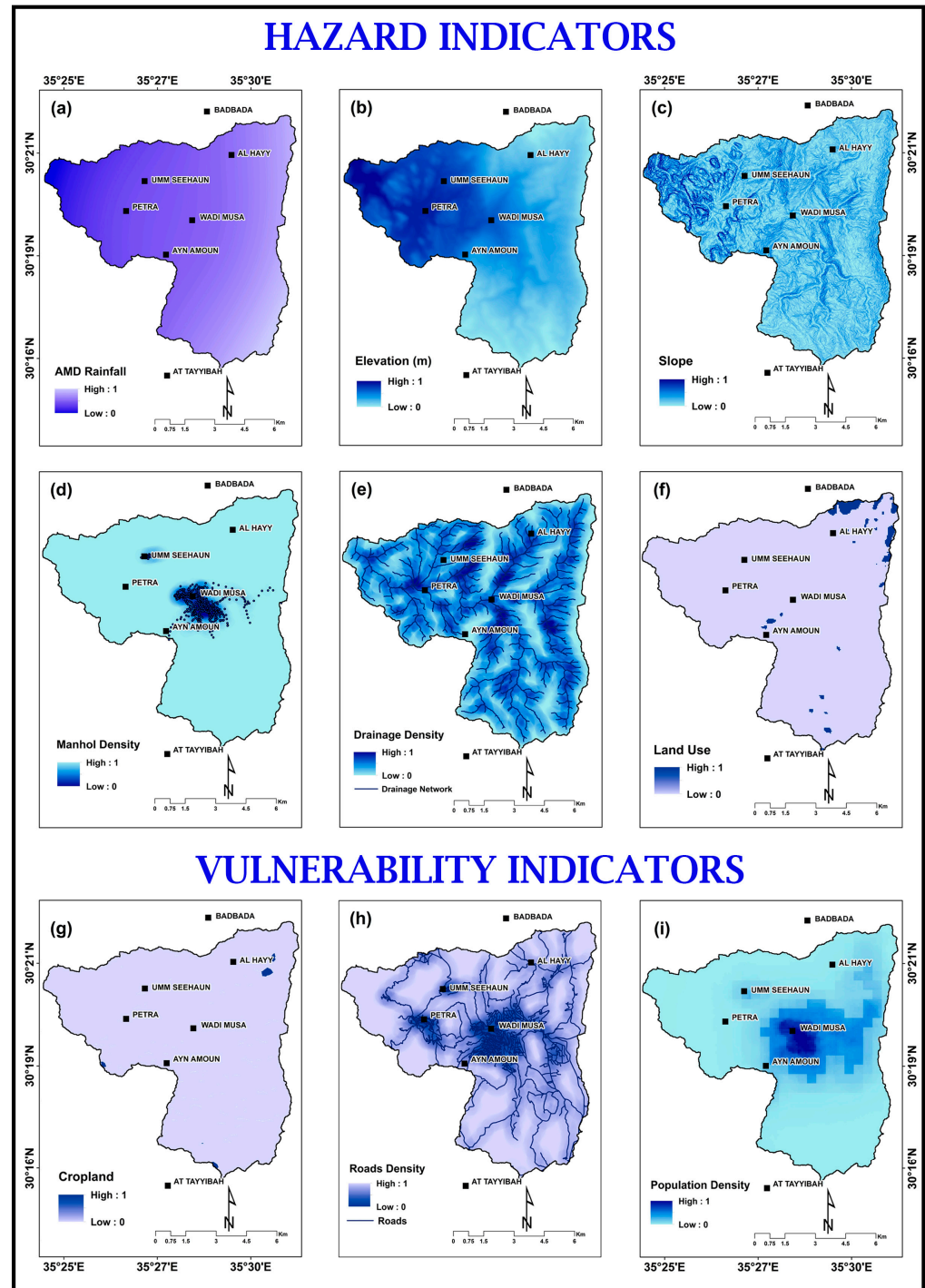


Figure 12. The thematic standardized maps for the hazard and vulnerability indicators, (a). Rainfall Intensities, (b). Elevation, (c). Slope, (d). Flood Control Points, (e). Drainage Density, (f). Land Use/Land Cover, (g). Cropland, (h). Transportation, and (i). Population Density.

13.2. Flood Risk Parameters

Because the indicators have different measurement scales and that their relationships to flood risk are also different, all input layers for all parameters need to be standardized from

their original values to the value ranging from (0–1). As a result, various standardization techniques were used on the indicators. In order to standardize the input maps, a series of equations that take into account the relationship between each indicator and flooding can be employed to transform actual map values to a range between 0 and 1. Some of the variables were correlated positively with flood danger, while others were correlated negatively. Positive and negative indicators underwent distinct standardization processes. According to Equation (8), the maximum technique (I) was applied to positive indicators, while according to Equation (9), the maximum approach (II) was applied to negative indicators [51].

$$\text{Normalized formula for positive indices : } v_{is} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (8)$$

$$\text{Normalized formula for negative indices : } v_{is} = \frac{x_{max} - x_i}{x_{max} - x_{min}} \quad (9)$$

For the indicator i , v_{is} is a standardized value, x_i is an initial value, x_{max} is the maximum value and x_{min} is the minimum value.

The likelihood of flooding depends on a number of topographic and meteorological features of a region. A comprehensive picture of flood hazard sensitive places with various magnitudes can be obtained by combining assessment of those aspects using modern methods. In this study, the analytical hierarchy process (AHP) model was used to map the flood danger map of the Petra catchment region, taking into account a total of nine geographical and climatic elements. The discussion of each of these elements and the outcomes follows. Thematically standardized maps for the Petra catchment area's hazard and vulnerability indicators are shown in Figure 12.

13.3. Hazard Indicators

13.3.1. Rainfall Intensity (RI)

The rainfall map demonstrated that the study area's eastern regions have the highest rainfall levels, and its western regions have the lowest quantities (Figure 12a).

The results of Table 10 support the initial hypothesis that rainfall intensities are the primary factor in determining flood hazards. This is because heavy precipitation over a short duration is the primary trigger for floods. The study used the average daily maximum rainfall to assess this parameter. The natural neighbor technique was applied to calculate the distribution of maximum daily rainfall, using the geostatistical analyst extension in ArcGIS. The rainfall map depicted that the eastern regions of the study area received the highest amounts of rainfall, while the western regions received the least (Figure 12a). The statement suggests that rainfall intensity is a crucial determinant of flood hazards. These findings have implications for flood risk management and planning in the study area.

13.3.2. Flood Control Points (FC)

Manholes are particularly successful at lowering the risk of flooding (negative indicator). The risk is reduced as manhole sizes and numbers are increased. To create the manhole density map, which will be utilized as a gauge for the flood control points' capacity to fend off disasters, a field survey was conducted. With ArcGIS, the Point Density function of the Spatial Analyst Tools was used to analyze the data (Figure 12d).

13.3.3. Drainage Density (DD)

A key idea in hydrological analysis is drainage density, which is calculated as the ratio of drainage length to basin size. WMS and ArcGIS were used to extract the drainage networks from the DEM. Utilizing the Line Density function in Spatial Analyst Tools with ArcGIS, it was possible to determine the drainage density of the streams. Within a radius surrounding each cell, this tool determines the magnitude per unit area [52] (Figure 12e).

13.3.4. Landuse (LU)

The rate of infiltration, the interactions between surface and groundwater and debris movement are all influenced by land use. So, while dense vegetation and forests encourage infiltration, pastures and urban areas encourage the flow of water over land. Eight main types—field crops, forests, tree crops, urban fabrics (high, moderate, and low), pastures, bare rocks and bare soil—cover a sizable section of the study region. These categories were ranked based on how closely they related to runoff generation (Figure 12f).

13.3.5. Vulnerability Indicators

Social, economic and physical indicators were divided into three groupings as vulnerability indicators. The population as the social vulnerability indicator, farmland as the economic vulnerability indicator and transportation as the physical vulnerability indicator were the three main variables that were taken into consideration.

13.3.6. Cropland (CL)

In any region, agriculture is vital to the economy and industries. Consequently, the amount of cropland was picked as an indicator [50]. The northeastern portion of the catchment region was where the farmland percentages were located (Figure 12g).

13.3.7. Transportations (Tr)

The maximum linear technique was used to standardize the density map after the roads density was determined using the Line Density (I) function in Spatial Analyst Tools with ArcGIS. The catchment area's middle and eastern regions were where the high-density areas were located (Figure 12h).

13.3.8. Population (P)

The number of people in each area was used to compute the population density. The projected total population per grid-cell was implied by the population density map that was being used. Using outputs from the Built-Settlement Growth Model (BSGM), the dataset was downloaded from the Department of Statics/Jordan [18] for 2021 [53]. The center of the catchment region was where the greatest population density was found (Figure 12i).

13.4. Flood Hazard Map

Using the natural breaking approach in ArcGIS, the final flood susceptibility map showed values ranging from 448 to 3955 that were divided into five distinct classes (Figure 13). The study region was divided into the classes of very low, low, moderate, high and very high chance of flood, which accounted for 13%, 24.20%, 30.95%, 22.5% and 9.24%, respectively (Figure 13).

The areas with the highest risk of flooding are in the western and central parts of the Petra catchment region, where the three main Wadis (Wadi Als-Sader, Wadi Khaleel and Wadi Al Moghare) meet and the slope abruptly increases at the base of the mountains. Higher sloped areas, on the other hand, are less prone to flooding. Therefore, an area's flood potential is greatly influenced by the elevation and slope. According to Zaharia et al. [54], areas with slopes more than 15° do not support water accumulation and the stagnation process, but areas with a thick canopy of dense vegetation and flat surface topography favor the retention of extra surface water during a flood.

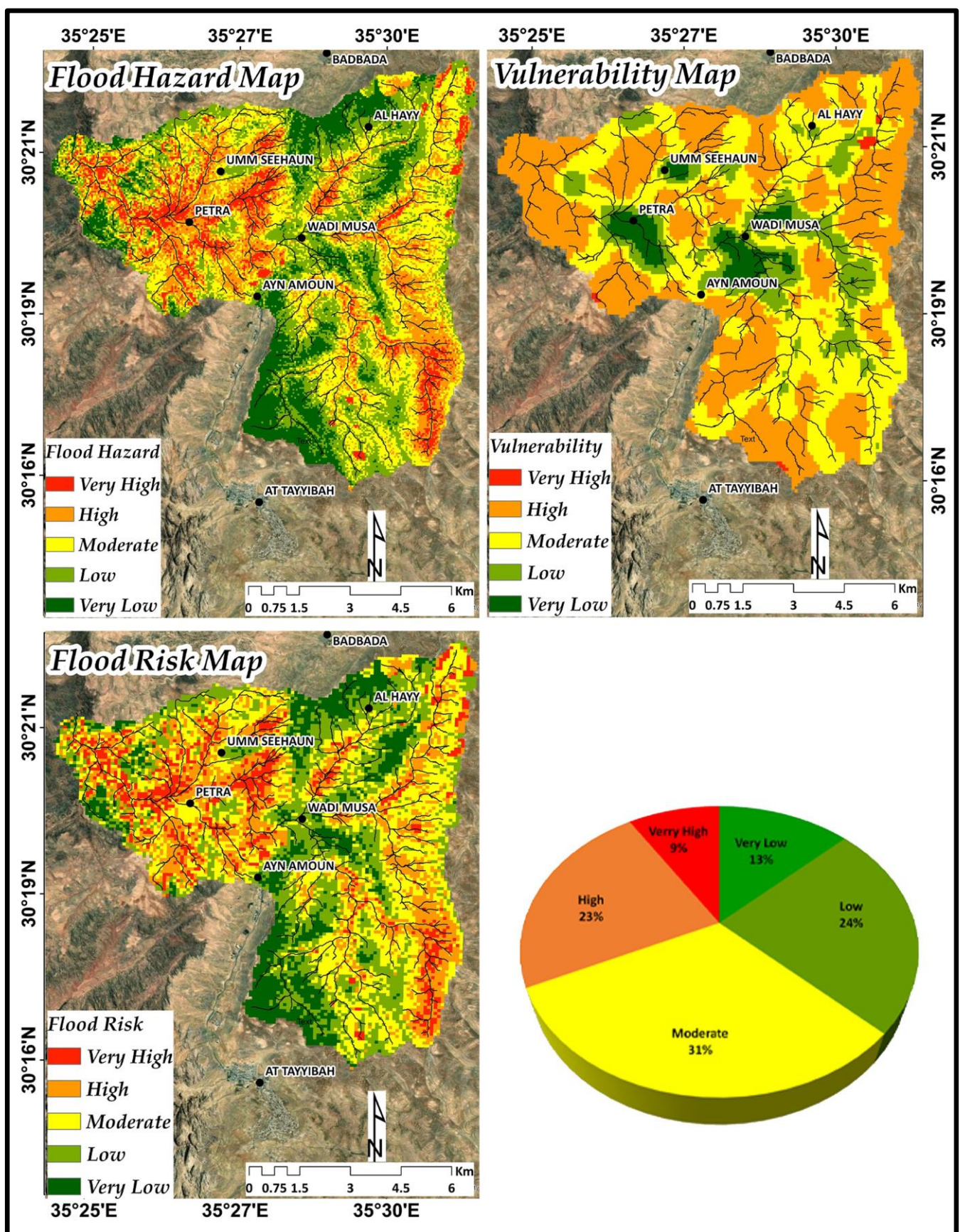


Figure 13. Flood hazard, vulnerability and risk maps.

Nearly 32% of the Petra catchment area exhibits high to very high flood susceptibility, while nearly 37% of the catchment area exhibits very low to low flood susceptibility. These regions are located south and north of the catchment's central portions. These regions, which are primarily interfluve zones and are concentrated in the eastern portion of the basin, have a moderate height, dissected structural hilly regions and are located in the center and western parts of the Petra catchment area. As the elevation in these areas ranges from 600 m to more than 1000 m and the slope exceeds 40 degrees, the eastern portion of the Petra catchment exhibits a high to very high potential for flooding. Sandstone canyons were formed in this region by granite and sandstone rocks from the Precambrian and Cambrian periods. These canyons are small, only a few meters wide and rise to a height of more than 90 m. Flash floods can form in these Wadis, and the water can surge more than 6–10 m. Although there is not much rain here—only 178 mm, on average—thunderstorms have nonetheless developed as a result of convective storm events in the Red Sea Trough [55]. Runoff can be produced during these events when it exceeds a threshold thought to be at an average of roughly 22 mm/day, making flash floods possible [8].

In the region, Al Qudah et al. [56] carried out rain-runoff experiments, demonstrating that runoff started between 10 and 17 min after 25 mm/h simulations were started. For the start of runoff, this translates to between 4 and 7 mm of rainfall. Additionally, they determined that the runoff coefficients varied from 16% to 91%.

14. Conclusions

This research focused on estimating flood hydrographs and volumes for the different return periods of 24 h storms in the Petra catchment area. Additionally, it aimed to develop a detailed hydrological map that outlines current flood risks, the potential impacts of flash floods and floodplain zones.

Utilizing the WMS software, a hydrological model of the Petra watershed was created, resulting in dividing the watershed into four sub-catchments. All morphometric parameters of these sub-catchments were calculated. In addition, the CN was calculated to be around 87. This model was calibrated and validated to predict peak discharge and volume for the seven different return periods (2, 5, 10, 25, 50, 100 and 1000 years). The peak flow for these periods ranged from 140 m³/s to about 553 m³/s, and the volume ranged from 1.65 to 6.45 MCM.

Nine indices, developed based on available data, analyzed flash flood characteristics related to risk and vulnerability in the area, guided by existing literature. The six risk indices included Elevation (E), Land Use/Land Cover (LULC), Slope (S), Drainage Density (DD), Flood Control Points (FCP) and Rainfall Intensity (RI). The three vulnerability indices were Population Density (PD), Cropland (C) and Transportation (Tr). The Analytic Hierarchy Process (AHP), a sophisticated statistical method, was used to assess the relative importance of each parameter. Rainfall intensity received the highest weight, while transportation received the lowest. The influence of each criterion was then summed linearly, producing a map that indicated highly susceptible zones. The methodology's effectiveness was validated through a statistical sensitivity analysis of the values assigned to the various criteria.

As a result, a flood susceptibility map was generated, showing that approximately 37% of the entire catchment area is at very high risk of flooding. Most of these high-risk areas are located in Petra and the nearby city of Wadi Musa. The methodology used in this study could serve as a guideline for flood management in Jordan and could be applied to similar research in other regions of the country.

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