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Flood Risk Map Using a Multi-Criteria Evaluation and Geographic Information System: Wadi Al-Mafraq Zone

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Abstract

This study aims to explore and identify the flood hazard vulnerability zones in Wadi Al-Mafraq (a Valley located in Jordan) using Geographic Information System (GIS) and Multi-criteria Design Analysis (MCDA). Six factors were taken into consideration to build a flood risk map in the study area. These factors include: distance from main channels, slope, elevation, land use/land cover, rainfall and drainage density. Different weights were assigned to each criterion based on its importance. MCDA was then employed to integrate these criteria to evaluate the study area based on its flood hazard characteristics. The study area was classified into five zones based on potential flood hazard vulnerability. The very-high flood hazard vulnerability represents 4% of the study area while high flood hazard vulnerability represents 9%. Very-low, low, and moderate flood hazard vulnerability represents 43%, 29% and 15%, respectively. It was found that the city center is located in the high and very-high flood hazard vulnerability zone. Results from this study provide a crucial input in disaster management process for local planning authorities. Appropriate decisions can be made based on the produced flood risk map in a timely manner ultimately leading to better disaster management and the protection of residents and properties.

Keywords: Geographic Information System; Multi-Criteria Decision Analysis; Flood Risk Management, Flood Hazard Map.

1. Introduction

Flood is considered as the most severe natural disaster in the world during the past decades, resulting in many environmental and socio-economic consequences within the affected flood plain. A flood is an influx of water that overflows land, and can destroy agricultural land, urban areas, and may lead to loss of life. Geographic Information System (GIS), Remote Sensing (RS), and Multi Criteria Decision Analysis (MCDA) are tools used in extracting models for flood threat tracking, risk analysis, and flood risk area recognition. This allows for adequate plan and control of this natural hazard (Youssef et al.,2011; Latu, 2009; Tran et al., 2009).

In 2004, Jordan's National Disaster Response Master Plan (NDRMP) described flash floods as one of the major hazards and potential threats (Farhan and Anaba, 2016). In the past half century, flash flooding incidents in Jordan have claimed the lives of 345 persons and affected 24,321 lives. Additionally, floods usually leave vast agricultural areas covered with mound water. Historical records show that flash floods threatened Petra, Dead Sea and Jordan Valley. This highlights the need for flood control and mitigation measures to protect visitors and the historical monuments (Farhan and Anaba, 2016).

Geographical Information System (GIS) is an organized system consisting of computer hardware and software, along with geographic data and trained staff (Ahn and Chon, 1999). It is designed to handle different data sets for specific geographic areas using the coordinates as the basis for an information system. The main function of a GIS is to input, store, organize, combine and analyze the ground referenced data and then to integrate these data with data from satellite imagery and other sources (Baban and Al-Ansari, 2001). Additionally, GIS is used to create maps, create 3D views, employ spatial analysis, retrieve data by location, class or attribute and handle visualization. GIS spatial analysis is a rapidly changing area, and GIS packages increasingly provide analytical tools as standard integrated facilities, as optional tool sets, as add-ins or as analysts (De Smith et al., 2007).

Multi-Criteria Decision Analysis (MCDA) is used in a GIS context to combine spatial data layers that reflect the criteria and determine how the layers are combined. In the 1960's, MCDA was designed to help decision-makers incorporate multiple alternatives that reflect the views of the actors involved into a future or retrospective structure. To help spatial decision-making, MCDA is used to incorporate qualitative and quantitative criteria and to define the degree and significance of the relationships between those parameters (Ocampo & Clark 2015; Abdelmoneim 2008;Massam 1988; Malczewski 1999). Decision-making is a systematic process of analysis of complex issues. The strategy is to divide a problem into small parts, analyze and aggregate each part to achieve a meaningful solution. The decision-making process is characterized as a choice of alternatives like GIS (Malczewski, 1999).

GIS applications in hazard mapping and evaluation have been important scientific fields in most world countries since the 1960's. Various GIS-based models were used in flood simulation, including the use of specialized GIS software such as SOBEK (Alkema, 2004a; Alkema, 2004b; Haile and Rientjes, 2005a), HEC-RAS (Rivera et al., 2007; Samarasinghe et al., 2010; Shamaomaet al., 2006), MIKE II, LISFLOOD, One-

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Dimensional Two-Dimensional (1D2D) hydraulic (Koivumäki et al., 2010) and TUFLOW (Evans, et al., 2007). Topographic maps have been used extensively to delineate the severity of floods (Evans et al., 2007; Forte et al., 2005; Ishaya et al., 2009). The used maps scale ranged from 1:50,000 to 1:250,000. It is popular to apply hydrodynamic physical modeling in flood hazard studies. Popular applications of models requiring many stringent controls (sensitivity analysis, scientist calibration and validation) (e.g., Alkema (2004); Haile and Rientjes (2005a,2005b)). These models require field and data checks, some of these studies use GIS, RS, MCDA in flood risk management and assessment. Studies conducted by Doorga et al. (2022), Msabi & Makonyo (2021), Abu El-Magd et al. (2020), Shafapour et al. (2019), Argaz et al. (2019), and Mundhe (2019), Syed et al. (2017), Rahmati et al. (2016), Danumah et al. (2016) and Franci et al. (2016) highlight the importance of flood profiling and risk management in all regions of the world.

2. Materials and Methods

2.1. Description of Study Area

Jordan is a developing country located off the Mediterranean Sea's South-Eastern coast between 35° and 39° East longitudes and 29° and 33° North latitudes. It is situated in an arid to semi-arid region where about 90% of its land receives an average rainfall of less than 100 mm/year, while only 3% of the land receives an average annual rainfall of 300 mm (Zeyad et al., 2008). The study area is located in the Northern part of Jordan to the west of Mafraq city. The study area selected for this research covers 317.242 km^2. Several studies were reviewed to obtain a good overall understanding of the study area regarding groundwater, land use and land cover, climate, rainfall, evaporation, temperature, topography, soil, surface hydrology and geology (AL Abbadi and Smadi, 2000; Department of Meteorology, 2015; Allison et al., 1998; Rimawi et al., 1999; Al-Ansari and Baban, 2001; Al-Adamat et al., 2007; Dutton and Shahbaz, 1999; Millington et al.,1999; Salameh et al., 1997; Waddingham, 1994; Allison et al.,2000).

2.2. Data Collection

To describe the study area, several GIS layers were gathered. The major GIS layers used to map spatial data include (a) rainfall, (b) geology, (c) soil, (d) climate and (f) hydrology. The secondary data were collected from various national organizations working in Jordan. Data includes digital maps in addition to integration of physical and socio-economic aspects of the study area.

2.3. Criteria for Flood Hazard Vulnerability Mapping

Criteria identification is useful for determining the degree of significance of topographic variables in flood hazard vulnerability (Malczewski, 1999). After consideration of previous studies assessing the associations between multiple criteria and flood risk, six were selected, namely, rainfall, slope, channels, drainage density, elevation and land use and land cover (Müller et al., 2011; Mmom and Ayakpo, 2014; Sowmya et al., 2015, Mundhe, 2018). Table 1 summarizes the criteria, weight and rating for flood hazard vulnerability within the study area based on literature review.

In this study, a simple modeling framework was adapted, where the model of a flood hazard vulnerability consists of two components. The first component discusses the upstream hydrology of the watershed, where a hydrological model is built to determine how much runoff is generated during a rainfall event. This will determine the behavior of water coming from the upstream watershed as it enters the main Wadi and downstream towards the city center. The second component deals with the Wadi and flood hazard vulnerability which aims to determine the criteria that affect the flood hazard vulnerability by using MCDA in GIS environment in the study area.

Based on these two combined components, a flood hazard forecasting tool was developed, which can be used to predict many flood-related problems. Insights into the possibility of flooding following runoff produced by rainfall, location and timing of flooding, and the depth of water during flooding may be gained.

Figure 1 shows the methodology of this research which involves: image pre-processing, image classification, data collection and verification, multi-criteria decision analysis. All data that has been collected in this study are processed, analyzed and integrated through GIS and MCDA to create a database of spatial and hydrological data. This database was then utilized in the development and calibration of the flood model to generate flood hazard vulnerability map in the study area.

2.4. Data Analysis

Digital Elevation Models (DEMs) were used to determine drainage networks and outflows of basins. Generating drainage networks from DEMs is dependent on gravity; using the steepest descent, water can flow from higher to lower elevation and no accumulation, evapotranspiration and groundwater depletion are expected. Automated extraction methods are the most effective approaches when the size of the DEM cells is significantly smaller than the dimensions of the watershed. In addition, GIS and remote sensing have been incorporated in the assessment of geo-environmental hazards in recent years.

Data employed in this study include: (1) Shuttle Radar Topography Mission (SRTM) data with a spatial resolution of 30 m, to verify the drainage networks derived from the SRTM; (2) Geological and topographical maps with a working scale of 1:50,000 used to understand the various unit distribution in the study area.

Arc Hydro tools (ArcGIS 10.4.1) were used to establish a framework for obtaining a deeper understanding of the drainage and watershed network in the region under review. Pre-processing of the landscape was used in the processing and development of the study area watershed basin. The DEM derived from SRTM data is used as a pre-processing reference for the terrain. Methods for removing the drainage network from DEM are well documented (Band 1986; Morris and Heerdegen 1988; Tarbotonet al.1991; Ghoneim and El-Baz 2007).

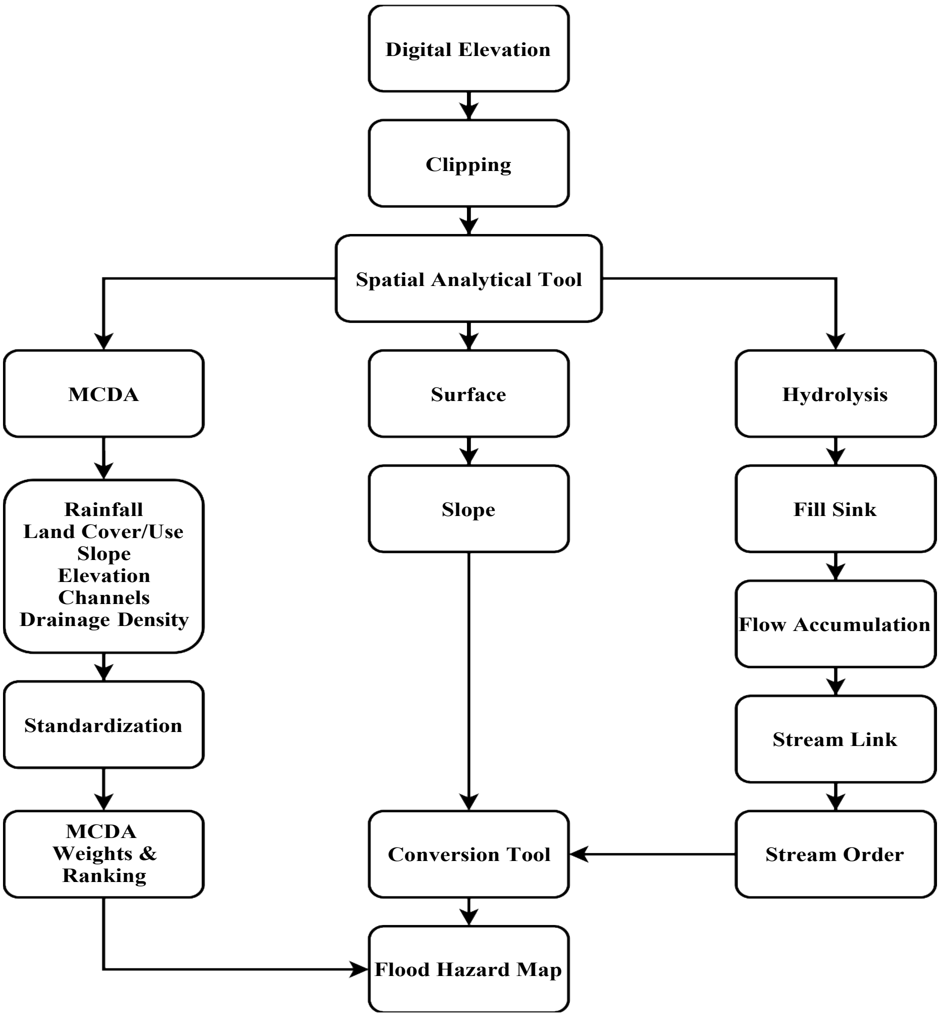


Figure 1. Analysis flowchart.

Table 1. The criteria associated with flood hazard vulnerability and their weights and ratings (Mundhe, 2018).

Criteria	Weight	Rating	
Landuseand Land cover.	31.00	Canal / Rivers and Lakes	4
		Built Up	3
		Agriculture/Scrub/Fallow	2
		Vegetation	1
Distance from Main Channels	24.90	<500	4
		500-1000	3
		1000-1500	2
		>1500	1
Drainage Density	16.68	>15	4
		15-7.5	3
		7.5-2.8	2
		<2.8	1
Rainfall (mm)	14.41	>300	4
		250-200	3
		200-150	2
		<150	1
Elevation	7.71	<560	4
		560-570	3
		570-580	2
		>580	1
Slope	5.14	<1.1	4
		1.1-3.0	3
		3.1-6.0	2
		>6.0	1

The following functions (in sequential order) are involved in Watershed pre-processing adapted from Fairfield and Leymarie (1991): DEM, Fill, Slope, Flow Direction, Flow Accumulation, Stream Link, Stream Order, Snap Power Point, Water Shed, Flood Hazard Vulnerability Map.

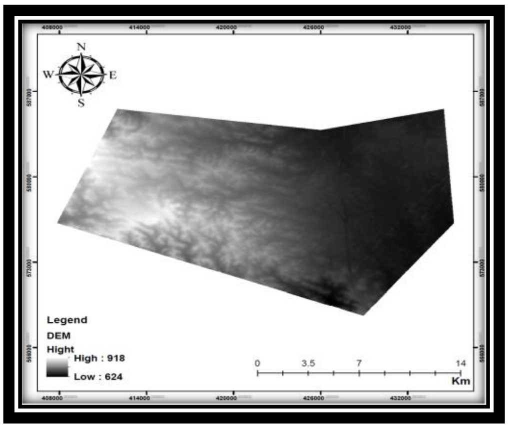
Image pre-processing and classification-in addition to data collection and verification- were processed, analyzed and integrated through GIS and MCDA to create a database of spatial and hydrological data. This database was then utilized in the development and calibration of the flood model to generate flood hazard vulnerability map in the study area.

2.4.1. Surface Hydrology Analysis

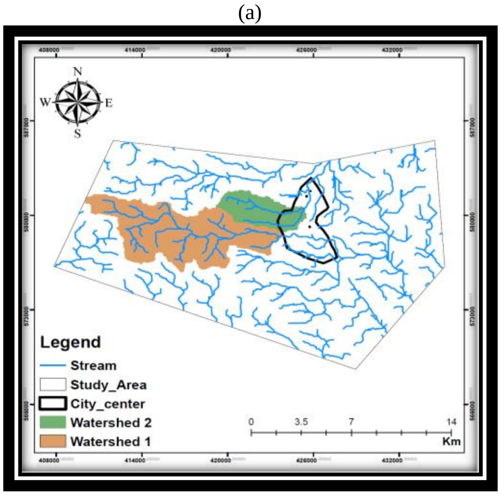
ArcGIS toolbox provided the approach and process needed to build flood simulation models. DEMs, SRTM, spatial analyst tool and management analyst tool on the ArcGIS toolbox were used to provide slope, contour, dimension, watershed etc.

GIS was used to determine the watershed map and runoff computation of the Wadi Al-Mafraq area (Figure 2(b) based on DEM map Figure 2(a)). This was achieved through the following steps:

1. Generate the Sink Fill map from digital elevation map
2. Generate the Slope map of the study area
3. Generate the Aspect map of the study area
4. Generate the Flow Direction map of the study area.
5. Generate the Flow Accumulation map of the study area
6. Generate the Watershed map of the study area.



(a)



(b)

Figure 2. (**a**) DEM Map; (**b**) Watershed for main Wadi.

2.4.2. Flood Hazard Vulnerability Mapping

There are two main Wadies (valleys) in the study area selected to calculate each of flow direction, flow accumulation, basin and watershed. The main aim of the surface analysis was to extract the catchment area of two main streams thus determining the amount of water in this basin which may cause flash flooding. The basin for the two Wadies is 53 km^2 with average rainfall amount of 300mm/year. The amount of water that accumulates in the basin toward the city center is about $15.9*10^6 m^3$.

Flood hazard vulnerability mapping focused on the six criteria: Distance from Main Channels, Slope, Elevation, Land use/land cover, Rainfall and Drainage density. Spatial maps were constructed and integrated using GIS and MCDA method.

Risk of flash flood hazard is higher in zones close to the Wadi's main channel and decreases moving further away. At the time of flooding, the surrounding area of the Wadies will be more affected. In the study area there are two main Wadies, the direction of these Wadies is coming from the Northwest of study area and converges both streams at the city center. Multiple ring buffers were created based on the distance from the Wadies' channel, then buffers were divided into four classes: high (distance <500m), moderate (distance from 500m to 1000m), low (distance from 1000m to 1500m) and very low (distance >1500m) (Figure 3(a)).

Drainage density is considered as one of the indicators for flash flooding, it is inversely related to permeability. The drainage density indirectly indicates the flood hazard to an area because of its relationship with surface runoff and permeability. The drainage density map was prepared using the line density analysis tool in ArcGIS. Drainage density map of the study area was classified into four categories based on flood hazard i.e.: very low (< 2.8), low (2.8 to 7.4), moderate (7.5 to 15) and high (> 15) and weights assigned them as 1, 2, 3, and 4, respectively (Figure 3(b)).

Rainfall plays a major role in flooding, with areas receiving more rainfall potentially under a greater risk of flash flood hazards than those with low rainfall. Rainfall map was prepared in ArcGIS environment. The rainfall map was classified into four classes: very low rainfall (<150mm), low rainfall (150mm to 200mm), moderate (200mm to 250mm) and high rainfall (>250mm) and weights assigned them as 1, 2, 3, and 4, respectively (Figure 3(c)). Maximum rainfall occurred in the Southwest part of study area.

Water runoff always flows from the high elevated areas to low elevated ones, causing floods to occur in lower areas. Higher elevation is found in Northwest and Southern part of the study area. Elevation mapping was created from DEM using spatial Analyst tool in ArcGIS. Based on flood hazard guideline, elevation map was classified into the four classes: very low elevation (<560m), low (560m to 570m), moderate (570m to 580m) and high elevation (>580m) (Figure 3(d)). Low elevation area was assigned the highest weights and high elevation region assigned the lowest weights.

Water velocity after rainfall is directly related to the angle of the slope over land. The output slope dataset can be calculated in percent or degree of slope (Jensen, 2004). There are four categories of the slope that can be identified and calculated using degree unit. The areas having a slope of < 2^o were assigned higher values, and the areas that had a slope between 2-4^o were considered as moderate. The areas that had a slope between 4-8^o, and more than 8^o were considered as low and very low consecutively (Figure 3(e)).

Land cover and use refer to the natural vegetation, water bodies, rock, soil, or artificial cover due to manmade activities. The Land sat 8 satellite images at a spatial resolution of 30m taken and made available by USGS in July 2019. They were used to collect data about the land use/land cover in the study area. This was made possible using the remotely sensed True Colors Composition (TCC), blue, green and red. All the layers that have been applied were integrated and supervised, and classification for the image was obtained using ArcGIS.

The classified land use and land cover map of the study area was classified based on flood hazard in four categories: urban, agriculture, bare soil and vegetation. The weights are assigned to these criterion as 4, 3, 2, and 1, respectively (Figure 3(f)).

3. Results

The flood models obtained in this study can be used to reconstruct flood events caused by heavy/torrential rains, and in mapping areas that were flooded. If an area previously experienced flooding, it is more likely that it will be flooded again in the near future. Then it is easy to determine which areas are to be avoided should heavy/torrential rains will pour over the area.

The flood hazard vulnerability map was generated by integrating the thematic maps of Channels, Slope, Elevation, Land use/land cover, Rainfall and Drainage density by the MCDA method. There are five class of potential flood hazard vulnerability in the study area. These include very low, low, moderate, high and very high flood hazard vulnerability as shown in Figure (4). The very high flood hazard vulnerability represents 4% of the study area, high flood hazard vulnerability represents 9% of study area. The very low flood hazard vulnerability represents 43% of the study area, the low for flood hazard vulnerability is 29%, and the moderate flood hazard vulnerability represents 15% of study area.

4. Discussion

In this study, the GIS and MCDA were applied to generate a flood hazard vulnerability areas map. Criteria affecting the flood hazard were defined based on literature reviews. MCDA and surface analysis indexes were used to identify and check the vulnerability of areas for flood hazard in the study area.

DEMs from the Shuttle Radar Topographic Mission (SRTM) was used to generate flood simulation model as an approach and process that was used to create these different models. Using spatial analyst tool and management analyst tool on the Arc toolbox to create each of slope map, aspect map, flow direction, flow accumulation, stream order and watershed.

Research results can be summarized as follow:

1. Slope: it is one of the main criteria that affects the flash flood where, water velocity is directly related to the angle of the slope over land. Areas with a high slope have a greater opportunity for create flash flood than areas with a low slope. The slope classes variations between 0 to 30 degrees, where the slope value that close to 0, is the city center area, this poses a risk of floodwater accumulation in city center.
2. Flow Direction: Creates a flow direction from Fill-DEM, from each cell to its steepest downslope neighbor. The output of the Flow Direction tool is an integer raster whose values range from 1 to 128. Flow Direction is one of the main parameters that affects the flow of flash flood trend.
3. Flow Accumulation: Creates an accumulated flow into each cell from the flow direction map. The flow accumulation result is a raster of accumulated flow to each pixel, as determined by accumulating the weight for all pixel that flow into each downslope cell.
4. Stream Order: Assigns a numeric order to stream a raster representing linear network branches. Stream Order output will be of higher quality if the raster for the input stream and the raster for the input flow direction is generated from the same surface. If the stream raster is extracted from a rasterized stream data set, the output may not be available because the direction will be on a cell-by-cell basis.
5. Watershed: A watershed is the set of cells whose downstream flow path passes through a selected cell (outlet). The main aim of the watershed to extract the catchment area of two main streams thus determining the amount water in this basin which cause of flash flood. The areas of basin for two wadies are 53 km^2 with average rainfall amount is 300mm/year. The amount of water that accumulation in basin toward the city center is about 15.9Mmc.

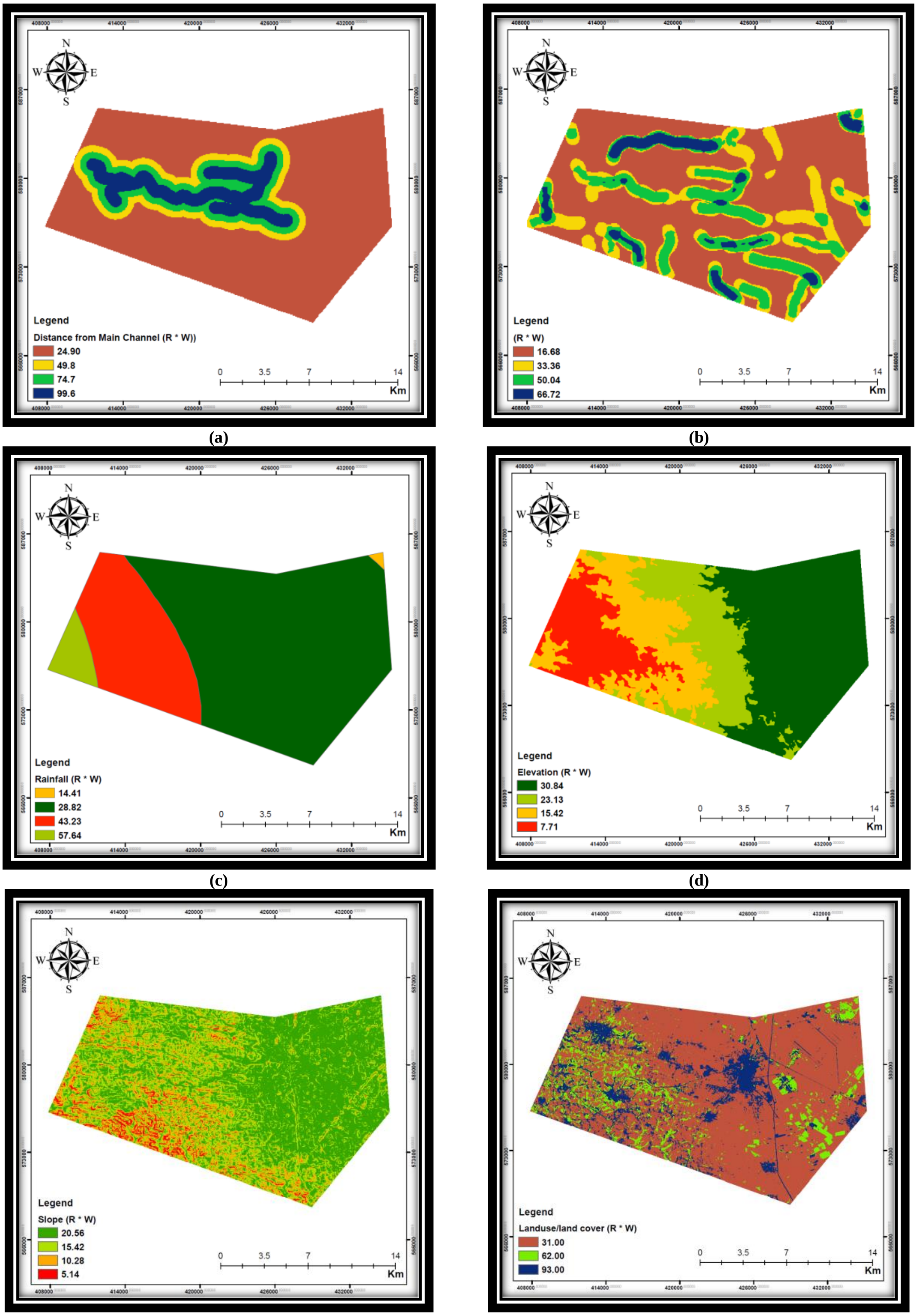


Figure 3. (**a**) Distance from Main Channels; (**b**) Drainage Density; (**c**) Rainfall; (**d**) Elevations; (**e**) Slope; (**f**) Land cover/land use maps.

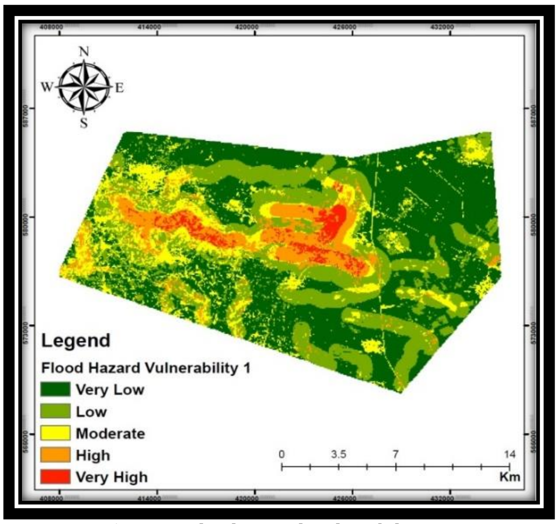


Figure 4. Flood Hazard Vulnerability Map.

4.1. Discussion of flood hazard vulnerability Results

Six thematic maps were added by the GIS and MCDA method. The flood hazard vulnerability map generated by integrating the thematic maps these are: Channels, Slope, Elevation, Land use/land cover, Rainfall and Drainage density. The criteria affecting the flood area and their weights assigned are based on literature reviews.

Based on Figure 3(a), the risk of flash flood hazard is more in zones close to the Wadi's main channel and its decrease the increasing distance. At the time of the flood, firstly the surrounding area of the Wadies is more affected. In the study area there are two main wadies, these wadies are coming from the Northwest, and the confluence of both streams is at City Centre.

Based on Figure 3(b), the drainage density indirectly indicates the flood hazard to an area because of its relationship with surface runoff and permeability. The drainage density map was prepared using the line density analysis tool in ArcGIS. Drainage density map of study area is classified into four categories based on flood hazard i.e.: very low (<2.8), low (2.8 to 7.4), moderate (7.5 to 15) and high (>15) and weights assigned them as 1,2,3, and 4, respectively.

According to Figure 3(c), the rainfall plays a major role in creating a flood situation because it determines the amount of water that falls. The rainfall map is reclassified into four classes: very low rainfall (<150mm), low rainfall (150mm to 200mm), moderate (200mm to 250mm) and high rainfall (>250mm) (Figure 2(d)). Lowest weight 1 assigned to very low rainfall category and highest weight 4 assigned to class of higher rainfall. Maximum rainfall occurs in the Southwest part of study area.

According to Figure 3(d), the Elevation criterion affects the flood situation. water runoff always flows from the high elevated area to low elevated area. Flood situation probably created in lower elevated flat areas compare to a higher elevation. Higher elevation is found in Northwest and Southern part of the study area. On the basis flood hazard guideline, Elevation map is classified into the four classes: high elevation (<560m), moderate (560m to 570m), low (570m to 580m) and very low altitude (>580m). Low elevation area was assigned the highest weights, and high elevation region was assigned the lowest weights.

Based to Figure 3(e), Slope is one of the main factors responsible for flood. Water velocity is directly related to the angle of the slope over land. There are four categories of the slope are identified and calculated as degree unit. The areas having a slope lower than two were assigned higher values and the areas, which had a slope among 2-4%, were considered as moderate. The areas that had a slope more between 4-8 % and more than 8% were considered as low and very low. This is summarized in Table 1, and the map shown in Figure 7.

Based to Figure 3(f), Land cover/land use is an essential factor for flood hazard mapping. Land use refers to man's activities and various uses which are carried on land. The classified land use and land cover map of the study area reclassified based on flood hazard in four categories: (urban, agriculture, bare soil and vegetation). The weights are assigned to these criterion as 4, 3, 2, and 1, respectively.

Based on Figure 4, there are five classes of potential flood hazard vulnerability in the study area. These include very low for flood hazard vulnerability, low for flood hazard vulnerability, moderate for flood hazard vulnerability, high for flood hazard vulnerability and the very high one. The very high flood hazard vulnerability represents 4% of the study area, high flood hazard vulnerability represents 9% of study area. The very low flood hazard vulnerability represents 43% of the study area, the low for flood hazard vulnerability is 29% and the moderate flood hazard vulnerability represents 15% of study area.

4.2. Flood Risk Assessment in Urban Areas Based on flood hazard vulnerability map

In the recent years, flash floods are considered one of the most important destructive natural hazards in Jordan. In the last years, the study area experienced floods with a semi-arid to arid climate and rainfall characterized by falls in the form of high intensity, short duration and irregular storms. Urban development is one of the most important human factors affecting flood occurrence. The flood risk map was created by combining the flood hazard vulnerability map with the land use map (urban map). It was found that the study area (city center) is located within high and very high categories of the possibility of a flood water accumulation. This is a serious indication of the possibility of a flood in any season in the study area. Based on the Figure 5, decision-makers must take all safety measures in the flood management to avoid a disaster by taking some of the recommendations contained in this research.

5. Conclusions

In this study, flood hazard vulnerability areas have been identified using GIS and MCDA methods. At first, a flood inventory map containing flood areas was prepared in the Wadi Al-Mafraq using MCDA, GIS and RS. The surface parameters analysis was used to understand hydrology analysis for study area. These represents of extract each of slope parameter, aspect parameter, flow direction, flow accumulation and watershed. Then, six spatial maps (Destines Channels, Slope, Elevation, Land use/land cover, Rainfall and Drainage density) were derived from the spatial database using MCDA. Using the mentioned conditioning criteria, flood hazard vulnerability maps were produced from map index calculated using MCDA method, and the results were plotted in ArcGIS.

Results from this research shows that there are five class of potential flood hazard vulnerability in the study area. The very high for flood hazard vulnerability represents 4% and high for flood hazard vulnerability represents 9% of study area. The very low for flood hazard vulnerability represents 43% of the study area, the low for flood hazard vulnerability is 29% and moderately for flood hazard vulnerability represents 15% of study area.

Based on flood Risk Assessment map in Urban Areas, the city center of study area is located in the high and very high for potential flood hazard vulnerability. This will pose a risk to the city's residents from the risk of flooding. Decision makers must take safety measures in disaster management to protect residents and property. These results are helpful for local planning authorities and planners to identify risk areas and make appropriate decisions in good time. The derived flood vulnerability map can provide a valuable tool for assessing flood risk for giving planers to insurance and emergency services.

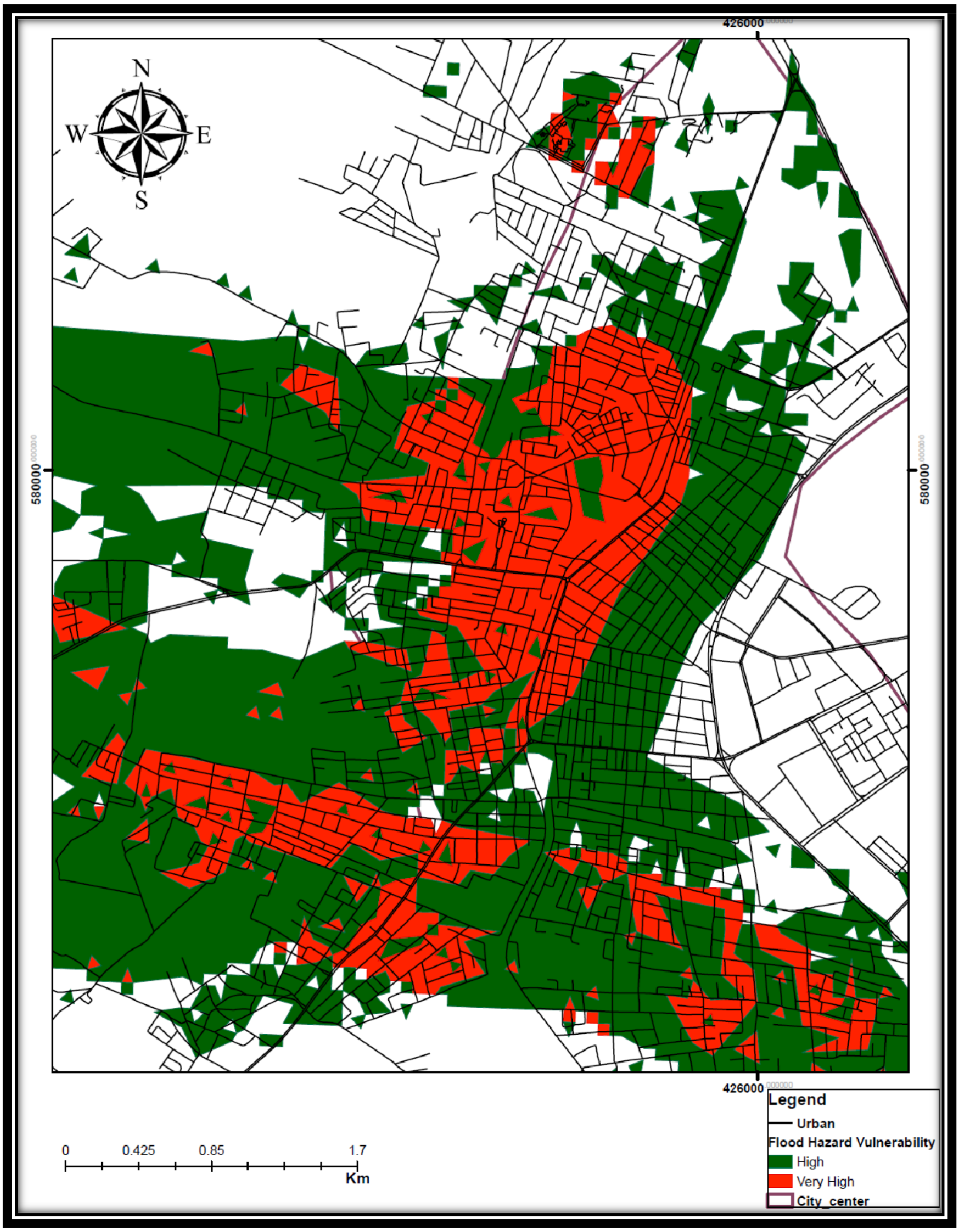


Figure 5. Flood Risk Assessment in Urban Areas.

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