

Article

Flood Risk Assessment of the Wadi Nu'man Basin, Mecca, Saudi Arabia (During the Period, 1988–2019) Based on the Integration of Geomatics and Hydraulic Modeling: A Case Study

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Abstract: This study aims to assess the impact of flash floods in the Wadi Nu'man basin on urban areas, east of Mecca, which are subjected to frequent floods, during the period from 1988–2019. By producing and analyzing the maps of the regions, an integrated approach to geomatics and hydraulic modelling is employed. The following maps are used: Flood-prone urbanity from 1988–2019, a flood risk map of Wadi Nu'man based on a risk matrix map, and a map of the proposed protection measures and alternatives in the study area. In order to achieve these goals, changes in the land use in the Wadi Nu'man basin were monitored by analyzing successive satellite images, taken by the US satellite, Landsat, in 1988, 1998, 2013, and 2019. Using a supervised classification, with the maximum likelihood method of ERDAS IMAGINE 2016, GIS was used in the production and analysis of soil maps, and geological and hydrological groups of drainage basins, as well as the hydrological model (HEC-HMS), were applied in calculating the hydrograph curve of the Wadi Nu'man basin. The flood water volumes and flow rates were estimated based on the SCS unit hydrograph, and the rain depth was analyzed and estimated for different periods. The hydraulic modeling program (HEC-RAS) was employed, when developing a two-dimensional model to calculate the speed, depth, and spread of the flood, in order to apply the risk matrix method. The recommendations based on this study give priority to the implementation of a flood prevention plan and the protection of infrastructure by maintaining the existing flood drainage facilities and establishing new drainage facilities to protect lives, property, and infrastructure.

Keywords: geomatics; wadi Nu'man basin; Mecca; hydraulic modelling; flood risk; urban areas; risk matrix

1. Introduction

Urbanization is the main cause of the changes that take place in hydrological and hydraulic processes and the occurrence of flooding in urban areas. It increases the total amount of runoff and its maximum flow [1–4]. Changes in the land use and land cover are affected by the human interference, such as the establishment of residential, industrial, agricultural, mining, and other infrastructure facilities. These are key processes associated with the economic and sustainable growth of any area [5]. The proper use of every part of the available areas of land is necessary for the improvement of the economic and planning status of such areas, without expanding the areas prone to risk, and this is essential for sustainable planning [5,6]. Changes of land uses and land covers, as well as their impact

on the hydrological processes, have recently been some of the most prominent research topics [7–9]. Geomatic techniques, such as remote sensing (RS) and the geographic information system (GIS), as well as their integration with hydrological and hydraulic modelling, are regarded as exceptional technical tools for the modelling and urban planning of flood hazards. In the current study, ArcGIS 10.7 was used to extract quantitative information based on hydrological and hydraulic modelling results (WMS and HEC-RAS). The interpretation of satellite images, taken during the period from 1988–2019, was put forward, considering the current sections of urbanization and employing the ERDAS IMAGINE program in order to link the interpretation with the current sections of urbanization and demonstrate how it was affected by the risk of sudden floods at different times.

The identification of flood-prone areas and the development of urban flooding maps based on geomatics and hydrological and hydraulic modelling are critical for the planning process and sustainable urban development [10,11]. Flood risk maps are useful tools for spatial planning and city development, particularly in an area where it is necessary to define infrastructure guidelines for the construction of a drainage network and to ensure strict adherence to these guidelines in the construction of new urban settlements [12,13]. Contemporary trends of integrated water management and planning in urban environments involve conducting a proper risk assessment and implementing a number of preventive measures that enable the control of rainwater and drainage water movement in all of the expected hydrological systems and their subsequent drainage through the water drainage system [14]. Technically, floods cannot be controlled without a suitable assessment through flood risk mapping [15,16].

Over the past few decades, flood modelling using the hydrological and hydraulic modelling [17] programs has evolved dramatically with the advent of GIS and satellite-derived remote sensing imagery, the emergence of high-resolution digital elevation models (DEMs) and distributed hydrological models, and the development of prediction systems and the real-time monitoring of the occurrence of flooding on the Internet, which was reflected in the high-accuracy mapping of flooding in urban areas.

Researchers [18–20] have used different methods and models to map natural hazards and assess the severity of sudden floods, and the five principal methods, according to the literature on flood risk modelling, are illustrated in Figure 1. Three of these methods are categorized under the morphometric methods in flood risk assessment: The Al-Shami method, the morphometric orders, and the severity level. These methods are suitable for the classification of the risks in the main and sub-basins, rather than for the classification of the risks in urban areas, and they are the most popular and most commonly applied in geographic research.

The fourth method is the multi-criteria analysis method, based on geographic information systems (GIS-MCDA), which is the method used most widely in geographic, schematic, and applied studies. It suits the modelling of the risk of flooding in urban areas, which depends on determining the criteria affecting the increased risk, and the criteria weights are based on the application of the hierarchical analysis method (AHP). A number of studies [21–25] showed that the AHP hierarchical analysis in the GIS environment is the most popular and the most powerful technique used in the production of flood risk maps, and it has a proper degree of accuracy and is suitable for other risk studies. Many AHP researchers describe it as an easy-to-use, cost-effective, and convenient way to assess flood risk.

The fifth method is known as the risk matrix method, which is based on the hydraulic modelling of the HEC-RAS program. It is considered as one of the most important and the best methods of modelling the risks of floods in urban areas, as it offers a two-dimensional model of the spread, depth, and velocity of the floods. These properties are not available in the single-dimensional model of the flood runoff [26–29]. While flood risk maps can be produced in multiple ways, the basic process is to use the results of the immersion analysis from single-dimensional or two-dimensional hydraulic models.

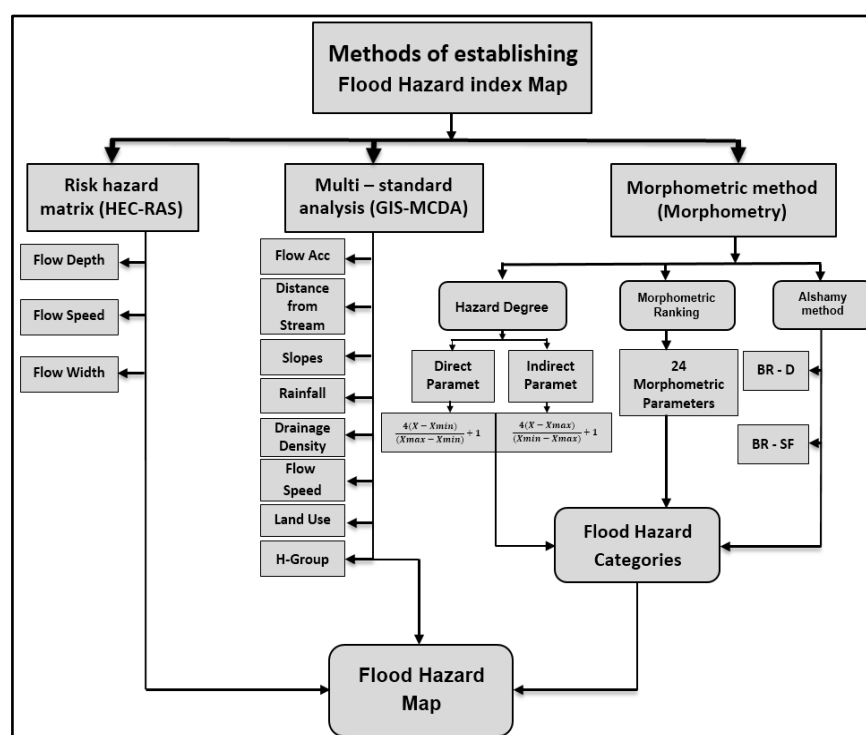


Figure 1. Methods of creating a flood risk index map.

The two-dimensional immersion model is more useful than the one-dimensional model in the creation of advanced flood risk maps that are used to predict flood damage in urban areas, as the two-dimensional models can produce spatially distributed information, including the flood depth and velocity, in an area that has been exposed to flooding [30–33].

The present study used a two-dimensional hydraulic modelling risk matrix analysis method, and the hydraulic modelling of the HEC-RAS program demonstrated a high efficiency in presenting a two-dimensional model of the spread, depth, and speed of the flood water. These characteristics are not available in the one-dimensional model of the floodwaters, and the two-dimensional model has the ability to identify urban areas prone to flooding and propose design strategies. To mitigate the effects of potential flooding is of great importance for political and planning decision-makers.

This study was conducted to assess the impact of the sudden flooding of the Wadi Nu'man basin on urban areas, east of Mecca, which are exposed to frequent floods. This area is of great importance for political and planning decision-makers due to the existence of several vital places: Mash'ar Arafa, in which about 3.5 million people gather annually to perform Hajj; the headquarters of the University of Umm Al-Qura in Al-Abedia; the populous district of Al-Awali; the Al-Husseinieh area, which is a place of agricultural and residential importance; and the railway station of Al-Mash'ar Al-Haram, between Arafa and Mena. Moreover, the most important arterial roads between Mecca and Mash'ar Arafa, and between Mecca and Al-Taif, lie in this area, in addition to several modern urban complexes and residential schemes. The main objective of this study is to assess the risk of the floods in the Wadi Nu'man basin of Mecca, Saudi Arabia, during the period from 1988–2019, based on the integration of geomatics and hydraulic modelling. This is achieved by determining the extent of floods in the Wadi Nu'man basin and identifying areas prone to flood, as well as linking them to the residential expansions that occurred during the period from 1988–2019.

An innovative approach was used for the Kingdom of Saudi Arabia, based on a combination of geographic information systems (GIS), remote sensing (RS), the watershed modelling system (WMS), the hydrological modelling program of the hydrological engineers program (HEC-HMS), and the analytical system of rivers at the Center of Hydraulic Engineering (HEC-RAS). Alternative preventive

measures in the area under study were proposed to help mitigate the impact of sudden floods of Wadi Nu'man on Al-Masha'er Al-Muqadasa, Umm Al-Qura university, and modern housing schemes.

2. Study Area

The Wadi Nu'man basin is located in the western region of Saudi Arabia, between the latitudes of $21^{\circ}28'28.76''$ and $21^{\circ}10'32.31''$ North and the longitudes of $40^{\circ}09'09.62''$ and $40^{\circ}09'46.17''$ East. The basin is about 7 km away from Mecca in the southeast direction, at the end of Al-'Abdia neighborhood, towards Ker. It is bounded in the north by Wadi Al-Bagidi and from the east by the heights of Al-Hada, while the mountain peaks, which represent the north-eastern upper edges of Wadi Malkan, are considered the southern and south-eastern boundaries (Figures 2 and 3).

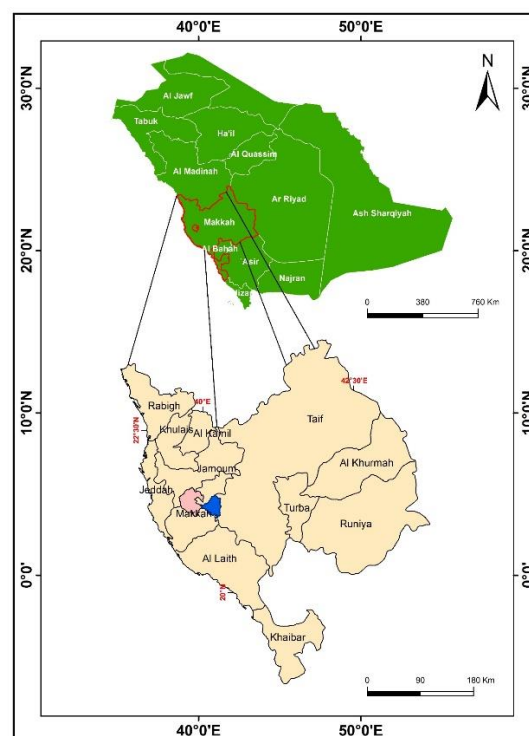


Figure 2. Wadi Nu'man basin in Mecca in 2019.

Wadi Nu'man has about eleven tributaries: The Al-'Abdia, Tan'ama, Zubaideh, Rehgan, 'ar'ar, al-'Arraja, Alshathkaa, 'alq, Taftafan, Ya'rug, and Alshar valleys. These tributaries feed from the Mothlam, Aktan, Sha'ar, Takbal, Kabkab, and Nu'man mountains (Figure 2). Wadi Nu'man has several sources from the peaks of Mothlam, Aktan, and Taftafan mountains, at a height of 1832 m above sea level, to the estuary in the area of the Al-Masha'er Al-Muqadasa, at a level of 272 m above sea level.

The area to the east of Mecca, which is represented by the Wadi Nu'man basin, is one of the most important and most developed parts of the city. Mash'ar Arafa, in which about 3.5 million people gather annually, lies in that part of the city. Moreover, the most important arterial roads between Mecca and Mash'ar Arafa, and between Mecca and Al-Taif, lie there, in addition to the headquarters of the Umm Al-Qura university, the populous neighborhood of Al-Awaleh, and the Husseinieh area, which is of great agricultural and residential importance.

Since the pre-Islamic era, this area has been an agricultural and aquatic hinterland for Mecca. Several changes have occurred in recent decades due to the continuous expansion of Al-Haram Al-Sharif, which was followed by the movement of the residents from the central area of Mecca to the outskirts of the city. Most of the areas of the Wadi Nu'man basin have become housing schemes and residential areas. Moreover, the agricultural land was cleared and converted into several slum schemes and planned schemes. Several urban areas and the infrastructure in the area under study were

exposed to recurrent floods of Wadi Nu'man. The most recent of these floods occurred on 3 November 2018, causing the destruction of many roads and the drowning of several urban settlements (Figure 4).

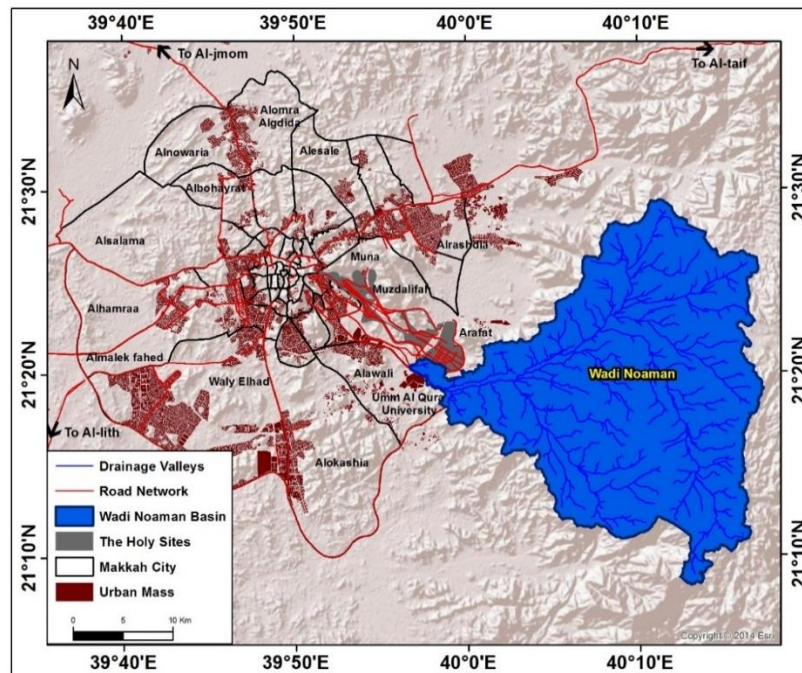


Figure 3. Wadi Nu'man basin in Al-Masha'er Al-Muqadasa in 2019.



Figure 4. Flooding in Wadi Nu'man in the east of Mecca on 3 November 2018. (a) Wadi Nu'man floods. (b) The exposure of the urban areas near Wadi Nu'man to drowning. (c–e) The effects of floods in the southeastern neighborhoods of Mecca.

3. Methodology and Data Processing

Figure 5 shows a flow chart of the methodology, which consists of three basic components that can be illustrated as follows:

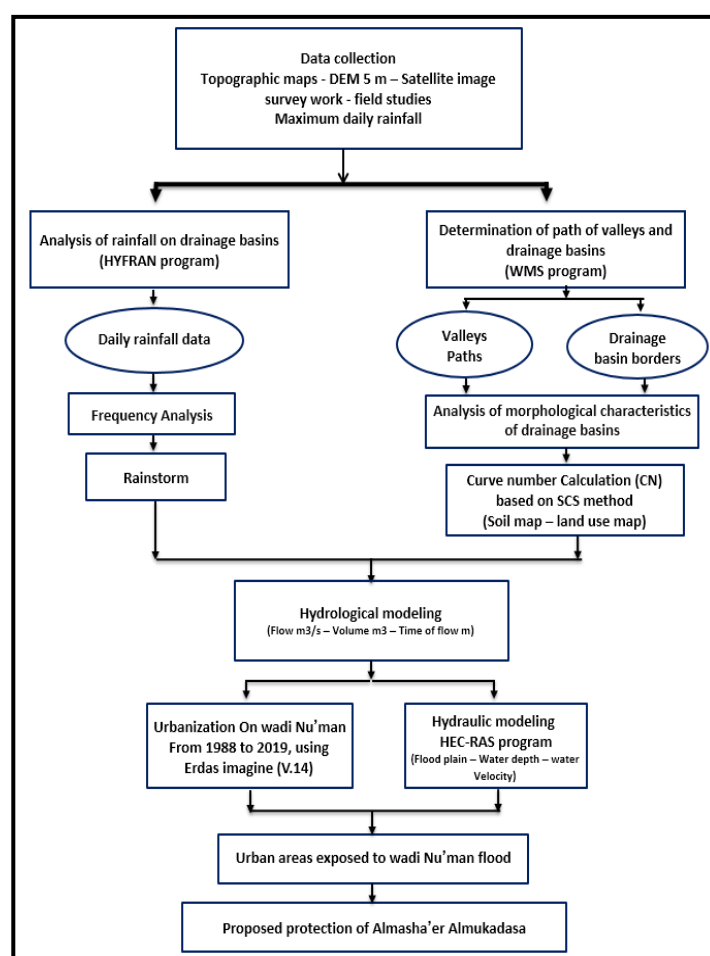


Figure 5. Methodology of the risk assessment study of the floods of Wadi Nu'man affecting Al-Masha'er Al-Muqadasa in 2019.

3.1. Monitoring the Land Use Changes in the Wadi Nu'man Basin during the Period From 1988–2019

To identify and monitor the land use changes of the Wadi Nu'man basin during the period from 1998–2019, the ERDAS IMAGINE 2016 program was used, and the process of monitoring the changes had four basic phases. The first stage consisted in the uploading of satellite images. Every ten years, images were taken by the United States Geological Survey Site (USGS) to monitor the changes that occurred in the Wadi Nu'man basin. The first image was taken in 1988; the second was taken in 1998; the third was taken in 2013 from a sensor TM, mounted on the American satellite, Landsat 4–5; and the fourth image was taken in 2019 from the mobile OL sensor I, mounted on the Landsat 8 satellite Table 1.

Table 1. The characteristics of the satellite images used in monitoring the urban changes of the Wadi Nu'man basin during the period from 1988–2019.

Date of Satellite Images Capture	Path	Row	Satellite	Spatial Accuracy	Sensor Type	Bands
11/1988	169	45	Landsat 4–5	30	TM	7
11/1998	169	45	Landsat 4–5	30	TM	7
12/2013	169	45	Landsat 4–5	30	OLI	11
8/2019	169	45	Landsat 8	30	OLI	11

The second stage dealt with a spectral enhancement. The last was performed to increase its spectral accuracy and reduce the spectral interference through the Raster menu, including the spectral

icon and the principal component option. The third stage dealt with the supervised classification. The process of the supervised classification was conducted using the maximum likelihood method from the Raster menu, involving the classification and the supervised classification options. Using the matrix, an accurate classification of the main Raster menu was made, involving the classification, including the supervised classification, and accuracy assessment options.

3.2. Hydrological Modeling

The HEC-HMS [14] has been applied to calculate the hydrograph curve in multiple ways, for both simple and complex drainage basins, by natural or artificial methods. It is one of the programs globally used in the field of hydrology and was developed by the American Army Organization. Using a 24-h storm design, the SCS TYPE II distribution was used, and the SCS method was used to calculate the delay and concentration times for different frequency times of 100, 50, 20, and 10 years. The output of the hydrological model used in our study was deduced to infer the hydrograph of the water's drainage basins.

The network of the valleys of the Wadi Nu'man basin has been identified and extracted using several different sources, the most important of which is the digital high-precision model of 5 m. The sources are from the website of King Abdulaziz City of Science and Technology, Institute of Space Research: Topographic maps at a scale of 1:50,000, with five plates, from the Saudi Geological Survey Authority; a modern satellite image from the Landsat 8/OLI, derived from the US Geological Survey Site (USGS); and a modern geological map at a scale of 1:250,000, derived from the Saudi Arabian Geological Survey (Figure 6).

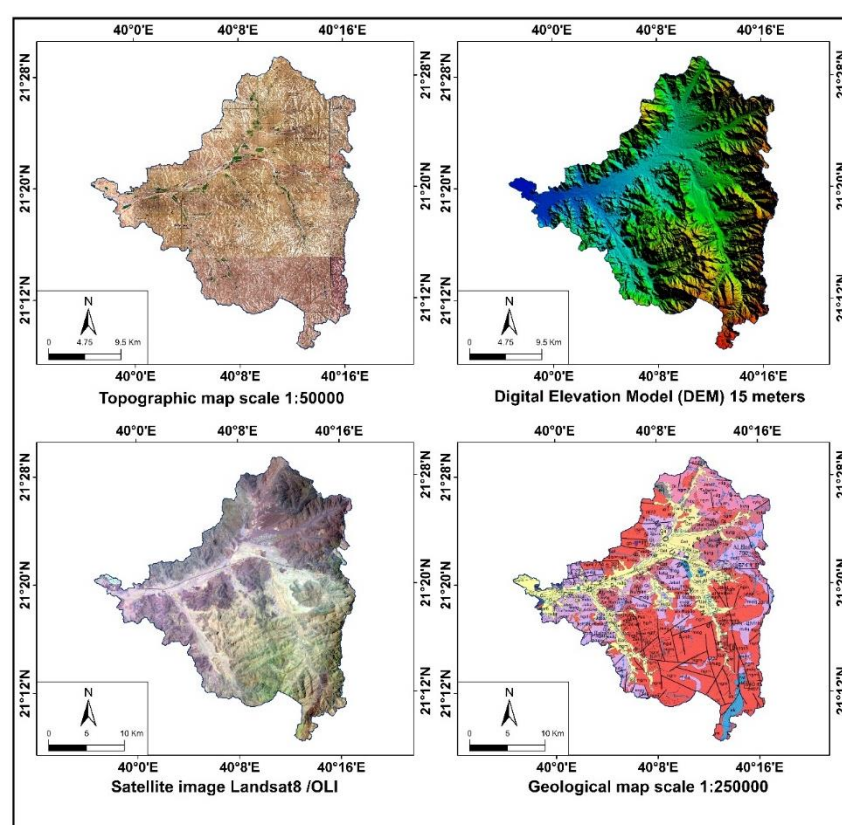


Figure 6. Some of the data sources that were used in the study of 2019.

It was necessary to use mathematical equations that represent the rain loss or link runoff and total rainfall and to calculate the curve number and the greatest drainage (m^3/s) (as illustrated in Table 2). The Kirpich equation [34] was used in the calculation of the time of concentration (Equation (1)),

which is the time needed for the rain water falling on the surface of the basin to gather, until it reaches the point where the flow is calculated. The delay time was calculated using the SCS method equation (Equation (2)), which is the time between the occurrence of a unit of rain and the occurrence of a unit of water runoff. The depth of rain or direct flooding in the basin was calculated to infer the total amount of floods at the actual rain value (Equations (3)–(5)). The amount of water in the area, before the occurrence of a flood, such as the water resulting from infiltration and rainwater found on plants, was also estimated using Equation (4). Equation (2) can be simplified, as illustrated in Equation (5). The maximum effort of the soil moisture was calculated using Equation (6), where the CN represents the curve number in the soil conservation services (SCS) method. This coefficient depends on the nature of the soil and land uses [35]. The maximum drainage (m^3/s) of each basin was calculated for different return periods using Equation (7), and the time of the greatest drainage was calculated using Equation (8). All of the aforementioned equations are illustrated in Table 2.

Table 2. Equations used in the current study.

Equation	Formula	Description
1	$t_c = 0.0195 \left(\frac{L^{0.77}}{S^{0.385}} \right)$	t_c = time of concentration (min); L = maximum flow distance (m); S = maximum flow distance slope (%); T_{LAG} = lag time (hour); Sr = maximum effort of soil moisture (maximum retention), calculated from the curve number (cm); Y = basin slope (%); P = rainfall for different return periods (cm); Ia = amount of water, before the occurrence of a flood, such as filtration and suspended rain on plants; qp = peak discharge (m^3/s); A = basin area (km^2); T_p = time until the peak (hour); Q = direct runoff (mm); and Δt = duration of designed stormwater
2	$T_{LAG} = \frac{L^{0.8} [Sr+1]^{0.7}}{1900 \sqrt{Y}}$	
3	$Q = (P - Ia)2 / (P - Ia + Sr)$	
4	$Ia = 0.2Sr$	
5	$Q = (P - 0.2Sr)2 / (P + 0.8S)$	
6	$Q = (P - 0.2Sr)2 / (P + 0.8Sr)$	
7	$qp = \frac{0.208AQ}{T_p}$	
8	$T_p = \Delta t/2 + T_{LAG}$	

3.3. Hydraulic Modelling

The two-dimensional hydraulic modelling was carried out using the HEC-RAS, version 5.0.4, of the Center for Hydrological Engineers, and the program can calculate the movement of sediments and chemical pollutants in the current, evaluate channels and passes, and assess the distal stalactites. The program is used in mapping the spread of floods and to calculate the risk of floods in threatened places. The applications of the program are used to calculate the rates of degradation and aggradation, resulting from the flood water currents, and the two-dimensional modelling of the program (HEC-RAS) was employed to calculate the speed, depth, and spread of the Wadi Nu'man's flood. The construction of the two-dimensional hydraulic model was achieved using the HEC-RAS, with four stages: (a) Correction or addition of engineering data for transverse sections and hydraulic structures; (b) peak flow of the data input; (c) general definition of the model plan (engineering data files and flow are set based on the results of previous hydrological modelling and the high 5-m digital height model; and (d) the implementation and verification of hydraulic calculations.

4. Results

4.1. Analysis of Rainfall in Different Return Periods and Determination of the IDF Curves of the Wadi Nu'man Basin

The precise determination of the amount of rain falling in the water basin is one of the most important factors that aid in the accurate calculation of the floods caused by these rains. It is also regarded as the proper basis of water statistics and the probability of the recurrence of floods. By referring to the records of the Stations of the Ministry of Water and Electricity and the general Presidency of Meteorology and Environmental Protection, it was found that Wadi Nu'man is affected by four meteorological stations: Al-Ferine (J 113), Al-Shifa (TA 109), Mecca (J 114), and Muntasaf-Huda (J 205). The records also revealed that these stations cover a period of 39 years, 54 years, 25 years,

and 47 years, respectively. The depth of the rain was determined in various return periods (5, 10, 20, 25, 50, and 100 years) using the Hyfran [36], and various statistical distributions, such as normal, log-normal, log-Pearson type III, Pearson type III, Gumbel, and exponential, and the Komogorov model, used to verify the results, were applied. It was concluded that the method (log-normal) is the most suitable for use in the four stations (Figures 7 and 8) (Table 3).

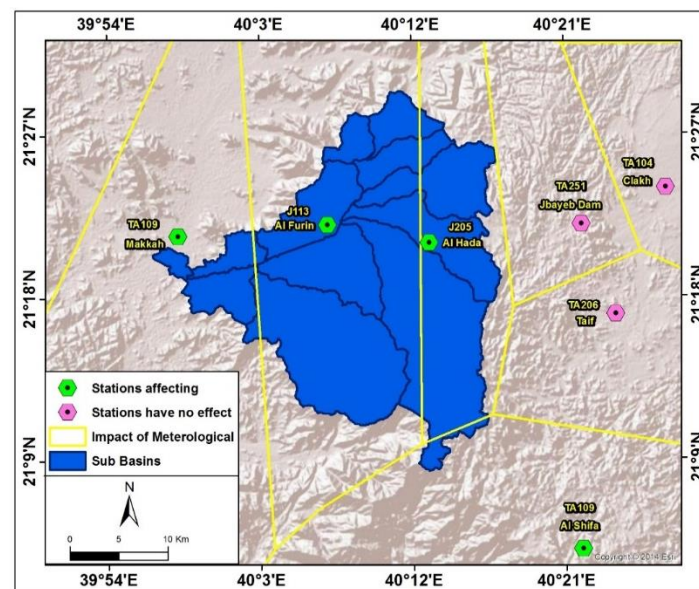


Figure 7. The locations of the rain stations, measuring the surroundings of the Wadi Nu'man basin using the Tyson polygons method in 2019.

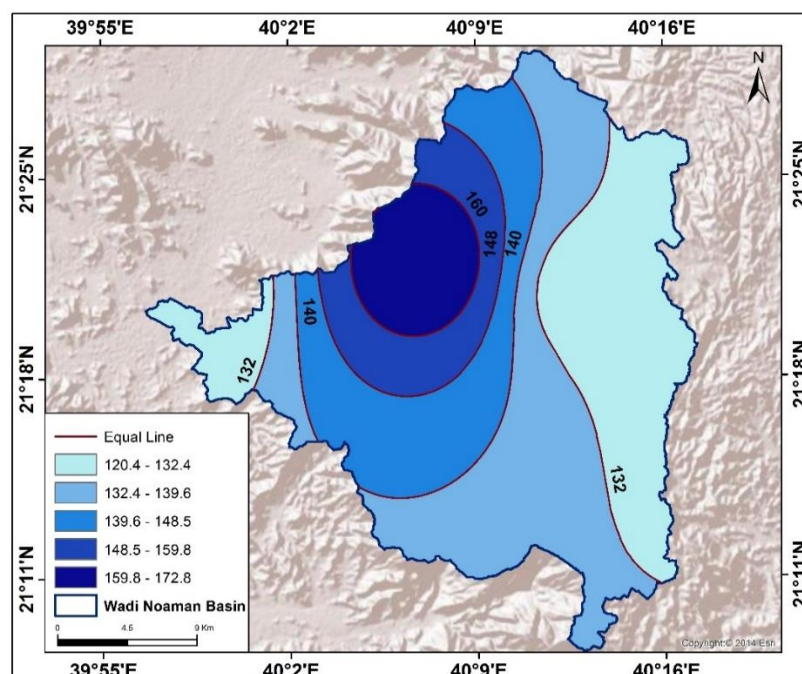


Figure 8. The annual rainfall iso lines of the Wadi Nu'man basin in 2019.

Table 3. The depth of rainfall in different return periods in the Al-Ferine (J 113), Al-Shifa (TA 109), Mecca (J 114), and Muntasaf-Huda meteorological stations (J 205).

Frequented Periods	2	3	5	10	20	25	50	100
Al-Ferine (J 113)	37.8	51.5	69.2	94.9	123	133	195	201
Al-Shifa (TA 109)	39.8	50.2	62.8	79.8	97.2	103	121	141
Mecca (J 114)	27.4	39.5	55.8	80.9	110	120	155	196
Muntasaf-Huda (J 205)	31.8	47.4	70.3	106	150	165	220	284

4.2. The Morphological Characteristics of the Wadi Nu'man Basin

The morphological characteristics (Figures 9 and 10) of the drainage basin were extracted using the watershed modeling system (WMS) through the drainage module by selecting “Compute Basins Data”, where the morphological properties of the basins were calculated automatically. These properties can be shown in the “Display option”, as the main basin, namely, the Wadi Nu'man basin, affecting Al-Masha'er Al-Muqadasa. The basin covers an area of about 688.6 km² and extends up to 38 km in length. The basin's slope is about 0.37214 m/m. The Wadi Nu'man drainage basin was divided into 12 sub-basins. The area of these sub-basins ranges from 8.6 km² to 174.3 km², while the lengths of the sub-drainage basins of Wadi Nu'man range from 6.4–27.4 km, and the gradients of the sub-basins range from 0.038021 to 0.463106 m/m (Tables 4 and 5; Figures 9 and 10).

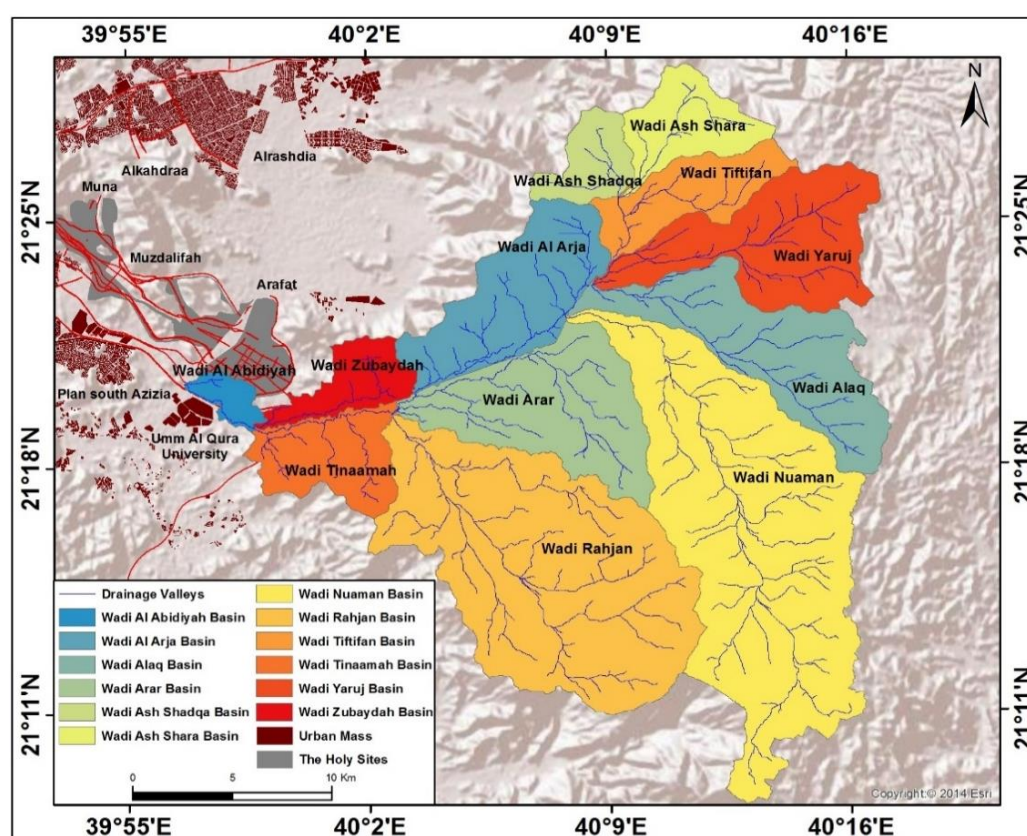


Figure 9. Sub-drainage basins of Wadi Nu'man affecting Al-Masha'er Al-Muqadasa in 2019.

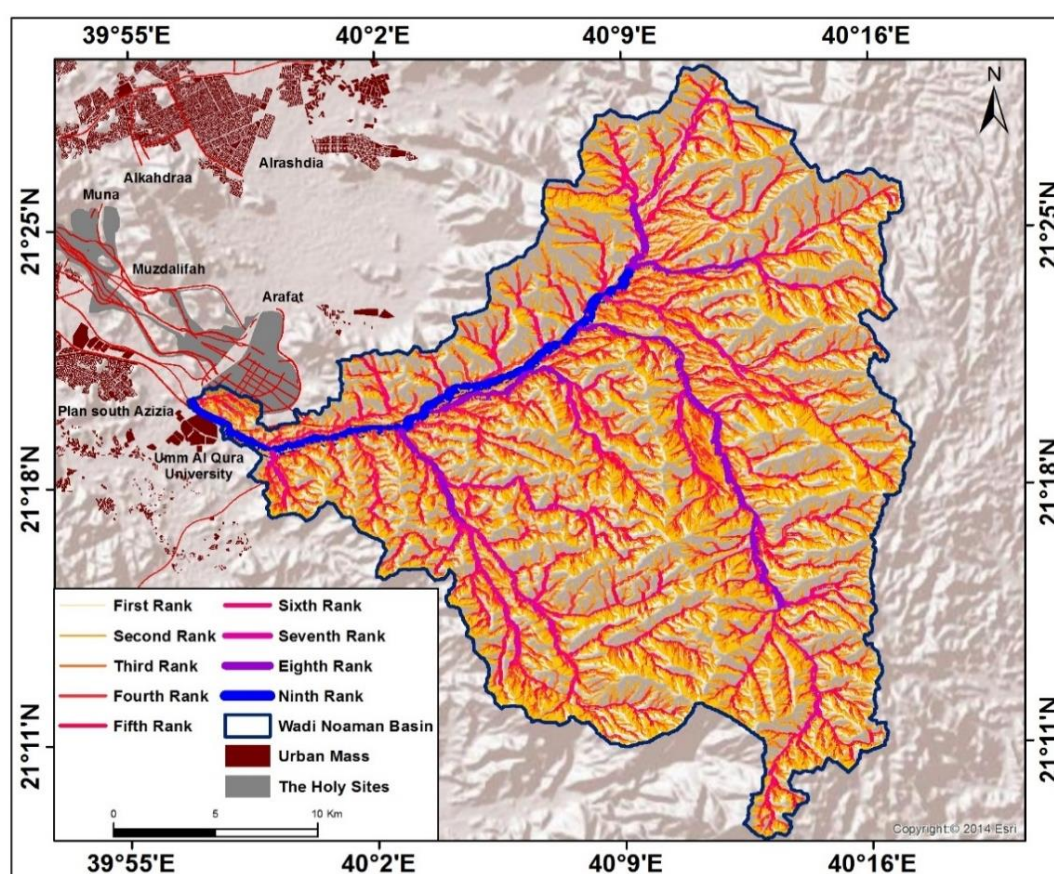


Figure 10. Map of the order of the valleys of the Wadi Nu'man basin in 2019.

Table 4. The most important morphological characteristics of the sub-drainage basins of Wadi Nu'man affecting Al-Masha'er Al-Muqadasa in 2019.

Basin Name	Area (Km ²)	Length (m)	Basin Slope (m/m)	Average Level (m)	Lag Time (Hr.)	Concentration Time (Hr.)
Wadi Nu'man	5.73	3.44	932.9	0.3721	38236.9	688.05
Sub-drainage basins of Wadi Nu'man						
Wadi Ash Shadqa	16.11	4858.08	0.379091	829	0.52	0.87
Wadi Ash Shara	25.19	8718.73	0.418357	939	0.88	1.47
Wadi Al Abidiyah	6.8	4584.29	0.038021	303	2.01	3.35
Wadi Al Arja	55.18	13,378.66	0.313703	696	1.47	2.45
Wadi Tiftifan	27.85	10,643.58	0.328909	868	1.18	1.97
Wadi Tinaamah	29.49	8047.17	0.224301	412	1.24	2.07
Wadi Rahjan	154.56	20,091.4	0.362424	853	1.68	2.80
Wadi Zubaydah	17.71	8723.15	0.210324	427	1.31	2.18
Wadi Arar	59.6	13,762.4	0.272599	585	1.66	2.77
Wadi Alaq	61.21	17,575.87	0.406956	1107	1.31	2.18
Wadi Nu'man	174.32	27,351.07	0.463106	1262	2.16	3.60
Wadi Yaruj	60.03	15,440.58	0.407025	1097	1.11	1.85

Table 5. The most important geometric and morphometric characteristics of the Wadi Nu'man basin affecting Al-Masha'er Al-Muqadasa in 2019.

Basin Name	Elongation Ratios	Circularity Ratios	Shape Factor	Merger Factor	Basin Slope	Sinuosity	Incubation Factor
Wadi Nu'man	60.87	1.6	0.5	2.3	0.39	0.19	0.5
Sub-drainage basins of Wadi Nu'man							
Wadi Ash Shadqa	22.1	1	0.4	1.76	0.47	0.33	0.7
Wadi Ash Shara	54.43	1.3	0.8	1.95	0.32	0.27	0.3
Wadi Al Abidiyah	64.67	1.2	0.8	1.99	0.32	0.26	0.3
Wadi Al Arja	82.62	1.3	0.8	2.21	0.31	0.21	0.3
Wadi Tiftifan	81.5	1.2	1	2.29	0.28	0.19	0.2
Wadi Tinaamah	102.02	1.5	0.5	2.02	0.38	0.25	0.5
Wadi Rahjan	226.16	1.2	0.7	1.86	0.35	0.29	0.4
Wadi Zubaydah	78.48	1.3	1.1	2.32	0.27	0.19	0.2
Wadi Arar	106.52	1.4	0.8	1.90	0.32	0.28	0.3
Wadi Alaq	124.41	1.1	1.3	2.34	0.25	0.19	0.2
Wadi Nu'man	99.81	1.3	1.1	2.32	0.27	0.19	0.2
Wadi Yaruji	146.33	1.1	1	2.18	0.28	0.21	0.3

4.3. Identification of the Hydrological Group of the Soils and Land Uses of the Wadi Nu'man Basin

One of the main coefficients in calculating the curve number (CN) is the identification of the hydrological group of soils and land uses, where the value of the curve number depends mainly on these two variables. Using the SCS method, four soil hydrological groups were identified [35]: A, b, c, and d. The Wadi Nu'man drainage basins are represented by the soil hydrological groups: A, b, c, and d. The soil hydrological group (A) represents an area of 50 km² and contains soils with a high permeability. The soil hydrological group (B), on the other hand, represents an area of 95.1 km² and contains alluvial soils, while the soil hydrological group (C) represents an area of 293 km² and consists of clay soils. The soil hydrological group (D) represents an area of 249 km² and consists of clay soils with a low permeability (Figures 11 and 12).

Land uses were also obtained by the classification of satellite images from the Landsat LANDSAT8/OLI using the ERDAS IMAGINE program. The land use layer was defined by the hydrological modelling program (WMS) through the insertion of a land-use layer, after defining the layers by selecting "New coverage" in the drop-down list of the GIS data and choosing "Add shape file data". There are three categories of land use in the Wadi Nu'man basin: The first category constitutes desert areas, with an area of about 533 km²; the second category constitutes agricultural areas, which represent 130 km² of the Wadi Nu'man drainage basins; and the third category represents urban areas, with an area of 27 km² (Figure 13).

4.4. Determining the Curve Number of the Wadi Numan Basin

The curve number (CN) method, which is one of the most common methods, was used to assess the amount of water loss through underground infiltration. This method requires three elements: The pre-condition of soil moisture, land cover, and soil hydrological groups. The value of the curve number ranges from zero to 100 and reflects the water response to the components of the land cover in the drainage basins, and it thus reflects the solidity of the surface. The closer the values to 100, the less solid the surfaces [37]. Thus, we find a difference in the value of the curve number of the sub-drainage basins of Wadi Nu'man, as the basin of Wadi Ya'rug came first in terms of the curve number, which reached 84.5, while Wadi Al-shathqaa came second in terms of the curve number, which was 84.1. The reason why the curve number values of these basins are high is that they are located in rocky areas. The basin of Wadi Al-'abdia, on the other hand, came last in terms of the curve number, which reached

77.1, since it is located in an alluvial area (Figure 14 shows the curve numbers of the basins of Wadi Nu'man).

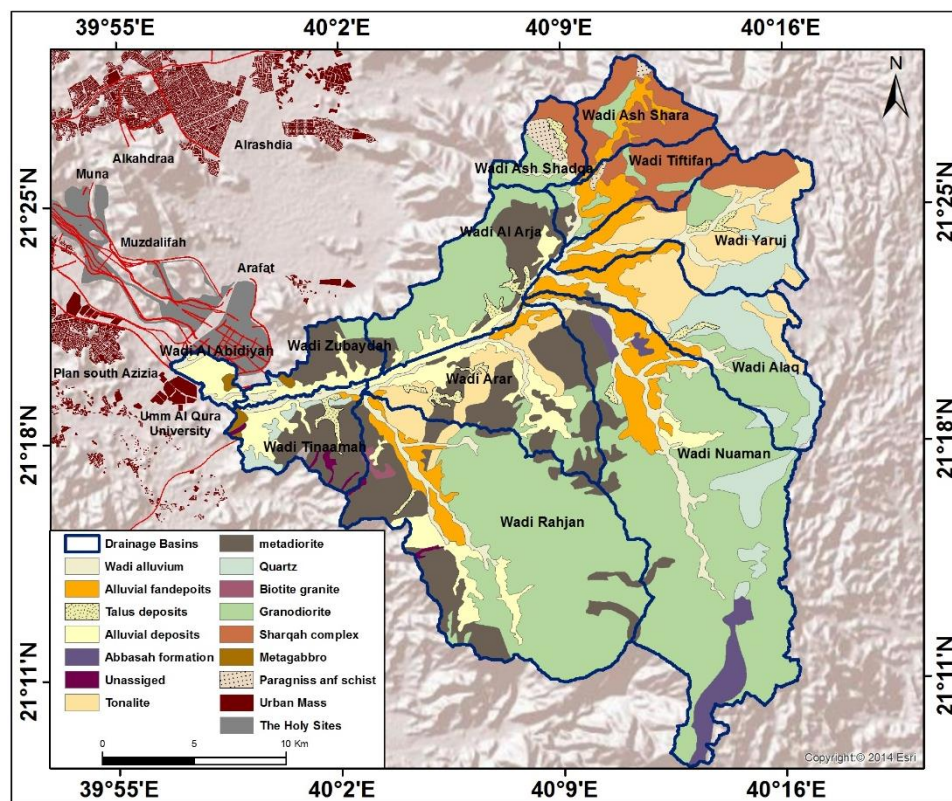


Figure 11. Geological map of the sub-drainage basins of Wadi Nu'man in 2019.

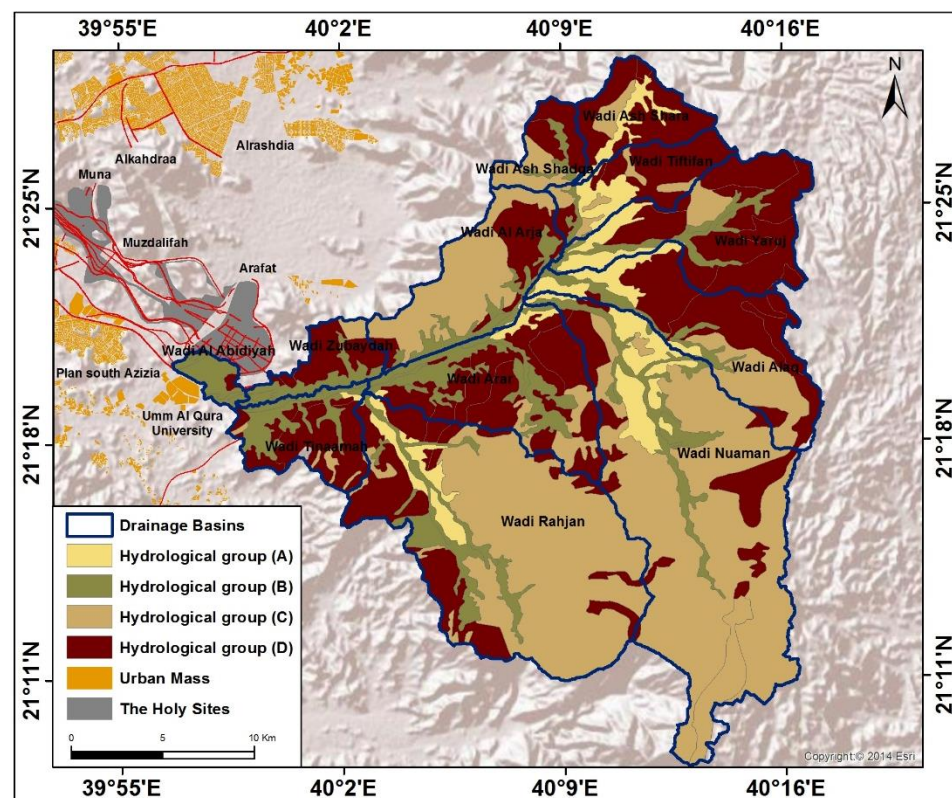


Figure 12. Soil hydrological group of the sub-drainage basins of Wadi Nu'man in 2019.

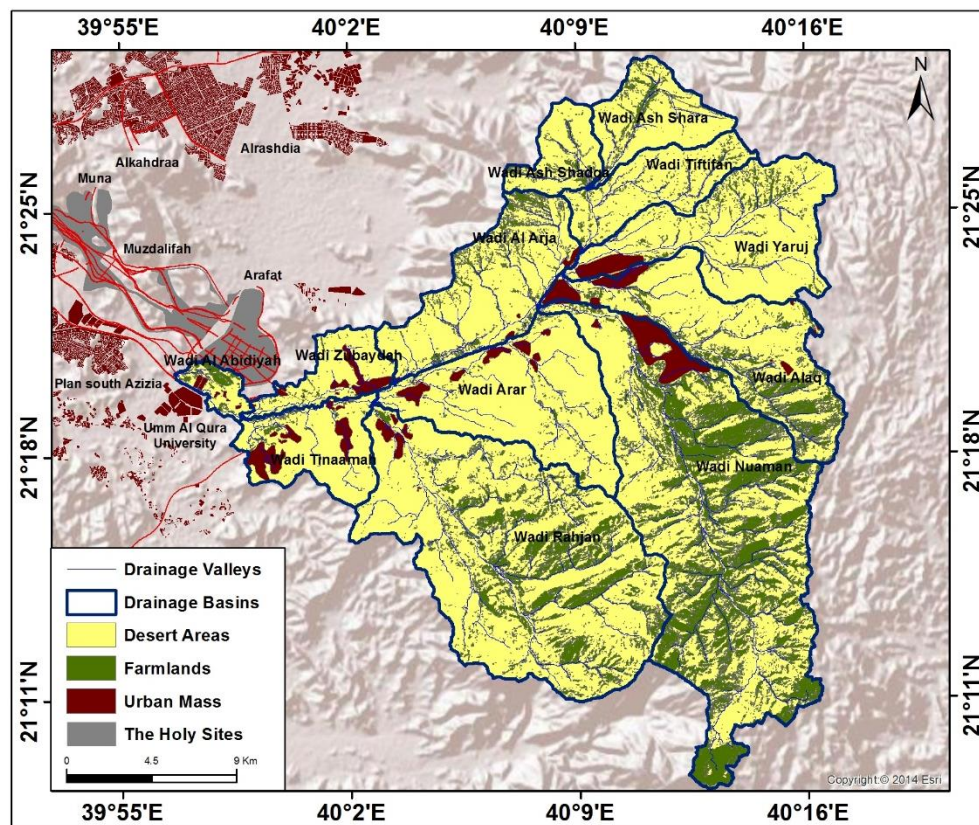


Figure 13. Land uses of the sub-drainage basins of Wadi Nu'man in 2019.

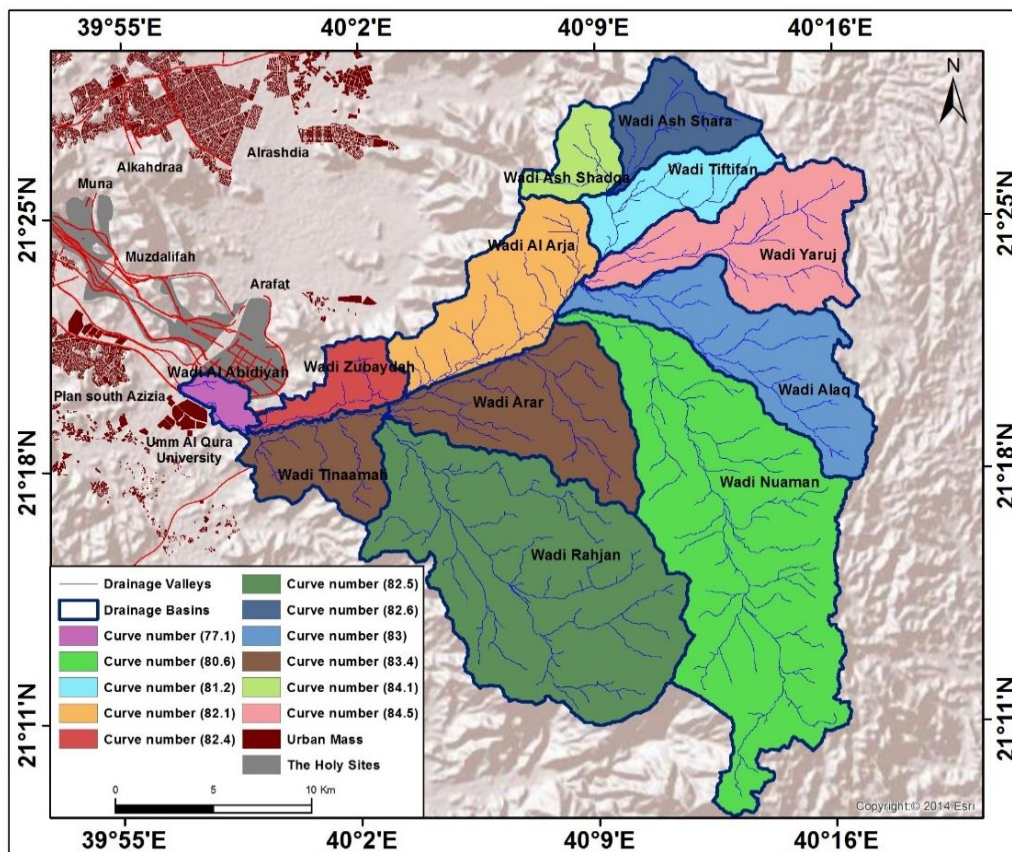


Figure 14. The curve number of the sub-drainage basins of Wadi Nu'man in 2019.

4.5. The Hydrological Characteristics of the Wadi Nu'man Basin (Flow (m^3/s); Flood Amount (m^3); Estimated Time of Arrival (Min))

The results of the analysis, shown in Table 6 and Figures 15 and 16, showed that the maximum drainage of the Wadi Nu'man basin reached about $2689.82 \text{ m}^3/\text{s}$; the amount of floods reached 66 million m^3 ; and the estimated time of arrival was 930 min during a return period of 100 years.

Table 6. Characteristics of the floods of the Wadi Nu'man drainage basin during different return periods.

Basin Name	Description	Return Periods (Years)				
		5	10	25	50	100
Wadi Nu'man	Peak discharge (m^3/s)	711.21	1128.46	1722.40	2191.08	2689.82
	Flood volume (m^3)	18,226,344	28,264,881.2	42,611,743.4	53,932,047.7	66,023,547.7
	Time of peak (min)	945	945	945	930	930
Sub-drainage basins of Wadi Nu'man						
Wadi Ash Shadqa	Peak discharge (m^3/s)	76.24	121.44	186.87	237.55	292.68
	Flood volume (m^3)	529,664.1	832,229.1	1,283,952.6	1,640,832.3	2,035,059.3
Wadi Ash Shara	Peak discharge (m^3/s)	71.27	114.17	175.38	223.15	274.23
	Flood volume (m^3)	687,553.2	1,069,935.3	1,621,029.6	2,056,193.1	2,526,299.1
Wadi Al-Abidiyah	Peak discharge (m^3/s)	4.68	8.81	14.90	19.94	24.76
	Flood volume (m^3)	90,472.9	158,688	25,362.2	337,792	414,884.3
Wadi Al-Arja	Peak discharge (m^3/s)	119.36	197.84	314.06	405.36	505.52
	Flood volume (m^3)	1,626,310.3	2,628,919.4	4,132,571.4	5,330,019.6	6,658,862.9
Wadi Tiftifan	Peak discharge (m^3/s)	57.82	93.31	144.22	184.81	228.18
	Flood volume (m^3)	690,534.4	1,083,256.6	1,649,115.4	2,097,625.5	2,580,491.7
Wadi Tinaamah	Peak discharge (m^3/s)	49.39	81.59	125.41	159.63	191.57
	Flood volume (m^3)	606,807.9	969,220.4	1,466,784	1,859,304.2	2,228,910.7
Wadi Rahjan	Peak discharge (m^3/s)	288.66	466.96	725.01	927.01	1144.85
	Flood volume (m^3)	4,335,680.7	6,844,352.4	10,513,884.2	13,420,902.2	16,588,303.7
Wadi Zubaydah	Peak discharge (m^3/s)	28.25	49.69	74.86	96.24	117
	Flood volume (m^3)	366,836.8	593,862.3	913,114.8	1,166,548.1	1,415,577.7
Wadi Arar	Peak discharge (m^3/s)	124.74	201.07	312.27	399.95	495.91
	Flood volume (m^3)	1,840,349.7	2,911,673.2	4,493,978.6	5,746,159.4	7,125,291.9
Wadi Alaq	Peak discharge (m^3/s)	123.44	189.78	279.99	349.72	421.65
	Flood volume (m^3)	1,563,109.6	2,338,974.9	3,402,043.7	4,231,067.4	5,093,199
Wadi Nu'man	Peak discharge (m^3/s)	207.82	33046	501.50	635.96	776.79
	Flood volume (m^3)	3,851,234.6	5,909,518.8	8,782,672	11,053,047.6	13,444,729.6
Wadi Ya'ruj	Peak discharge (m^3/s)	149.30	225.36	328	406.84	488.04
	Flood volume (m^3)	1,671,030.9	2,467,979.6	353,847.1	4,396,487.4	5,272,152.8

Regarding the sub-basins, the Wadi Rehgan basin came first in terms of the maximum flow during a 100-year return period of approximately $1144.85 \text{ m}^3/\text{s}$, followed by the Wadi Nu'man basin (approximately $776.79 \text{ m}^3/\text{s}$). On the other hand, the Al-'abdia drainage basin came last in terms of the maximum flow, which reached approximately $24.67 \text{ m}^3/\text{s}$, followed by the Wadi Zubaideh basin, whose maximum flow reached about $117 \text{ m}^3/\text{s}$.

The Wadi Rehgan basin came first in terms of the amount of flooding during a return period of 100 years, which reached about $16,588,303.7 \text{ m}^3$. It was followed by the Wadi Nu'man basin, whose flooding amount reached $13,444,729.6 \text{ m}^3$. Wadi Al-'abdia came last in terms of the amount of flooding, which reached $414,884.3 \text{ m}^3$, followed by the Wadi Zubaideh basin (about $1,414,577.7 \text{ m}^3$).

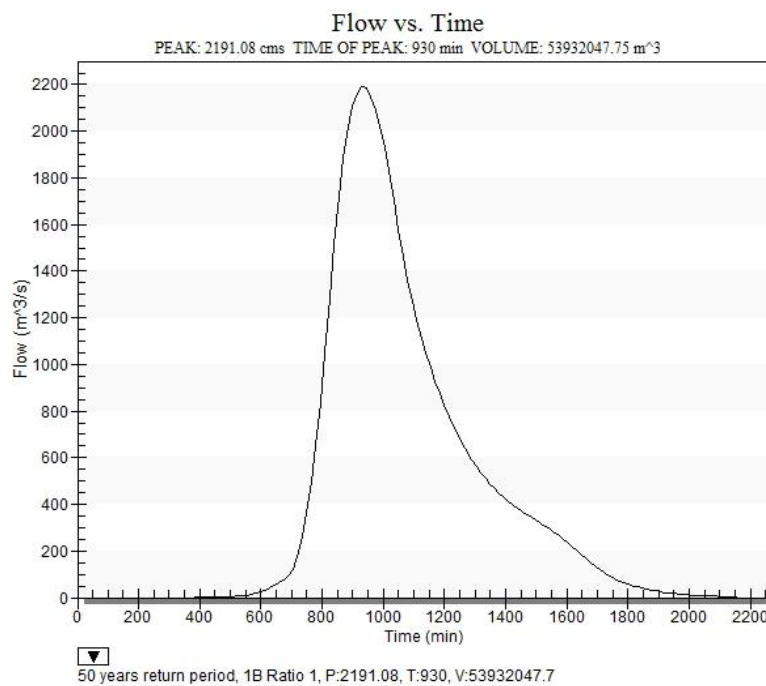


Figure 15. Hydrograph of the flood flows to the main Wadi Nu'man basin during a return period of 50 years.

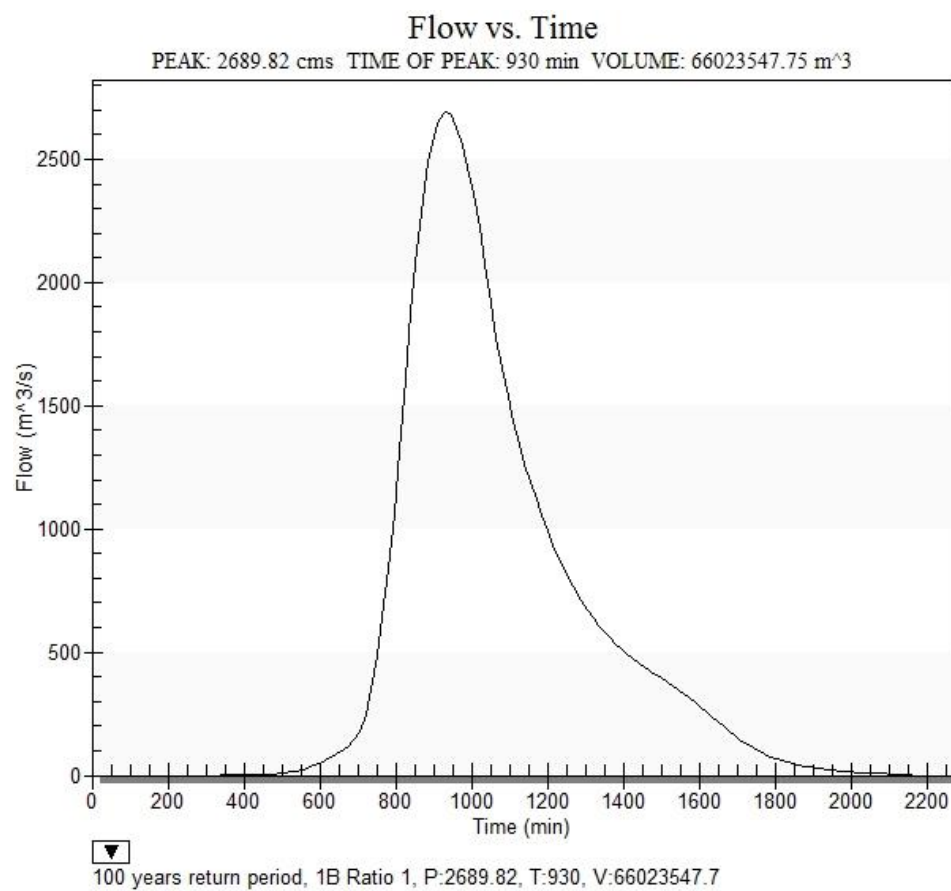


Figure 16. Hydrograph of the flood flows to the main Wadi Nu'man basin during a return period of 100 years.

5. Discussion

5.1. Monitoring the Changes in the Land Use of the Wadi Nu'man Basin during the Period from 1998–2019

The land-use change plays an important role in the hydrological behavior of drainage basins and affects the local hydrological cycle. Several studies have been conducted to assess the impact of land-use changes on the runoff [38–42]. Many authors have acknowledged the fact that increased urban activities in the flood areas will increase the apex drainage, reduce time to the apex, and increase the runoff [43–47]. A better understanding and assessment of land-use changes that have a direct impact on the processes of hydrological water catchments is crucial for the planning and sustainable development of water catchments [48–51]. The geomatics of remote sensing (RS) and geographic information systems (GIS) have recently been employed as powerful and effective tools in identifying changes in the land use [52,53]. In this study, four consecutive satellite images were loaded with a fixed separator every 10 years by the US Geological Survey (USGS) in order to monitor the changes in the Wadi Nu'man basin. The images were taken by the TM sensor on the American satellite, 4LANDSAT-5. The first image was taken in 1988; the second in 1998; and the third in 2013. The fourth satellite image was taken in 2019 by the OLI Sensor on the Landsat 8 satellite. The guided classification process was carried out using the method of the maximum likelihood. The classification accuracy of the satellite images was determined, and the time change of each classified phenomenon was detected using various calculations and quantitative indicators. These changes were measured by several scales, and Table 7 and Figure 17 show the results of monitoring the changes of the Wadi Nu'man basin during the period from 1988–2019.

Table 7. Changes in the land uses of the Wadi Nu'man basin during the period from 1988–2019.

Phenomenon	1988	1998	2013	2019	1988–2019
Vegetation (Km ²)	87.63	107.46	129.02	130.05	
Average of annual increase (Km ²)	-	2	1	0.17	1.37
Annual growth rate %	-	2.06%	1.23%	0.13%	1.28%
Urban mass (Km ²)	0.53	1	17.28	26.9	
Average annual increase (Km ²)	-	0	1	1.60	1
Annual growth rate %	-	6.55%	20.93%	7.66%	13.51%
Desert areas (Km ²)	599.9	579.6	541.76	531.11	
Average annual increase (Km ²)	-	−2	−3	−1.78	−2.22
Annual growth rate %	-	−0.34%	−0.45%	−0.33%	−0.39%

5.1.1. Vegetation

Applying the vegetation index (NDVI) to the satellite image of the area of the Wadi Nu'man basin in 1988, it was apparent that the vegetation, whose value exceeded 0.05, covered about 87.63 km², representing 12.74% of the total area of the Wadi Nu'man basin. Dense vegetation was concentrated in the south and northeast of the Wadi Nu'man basin, where there is a density of trees and plants on the high slopes, in addition to the existence of agricultural areas, located in the plains of Wadi Nu'man and its tributaries. In 1998, the area of vegetation, whose value exceeded 0.05, was about 107.46 km², constituting about 15.62% of the total area of the Wadi Nu'man basin. In 2013, the area of vegetation, whose value exceeded 0.075, was about 129.02 km², representing about 18.75% of the area of the Wadi Nu'man basin. In 2019, the area of vegetation, which exceeded 0.075, reached about 130.05 km², representing about 18.9% of the total area of the Wadi Nu'man basin. This shows that the annual growth rate during the period from 1988–2019, was about 1.24%, and the average annual increase during the same period was 1.3 km².

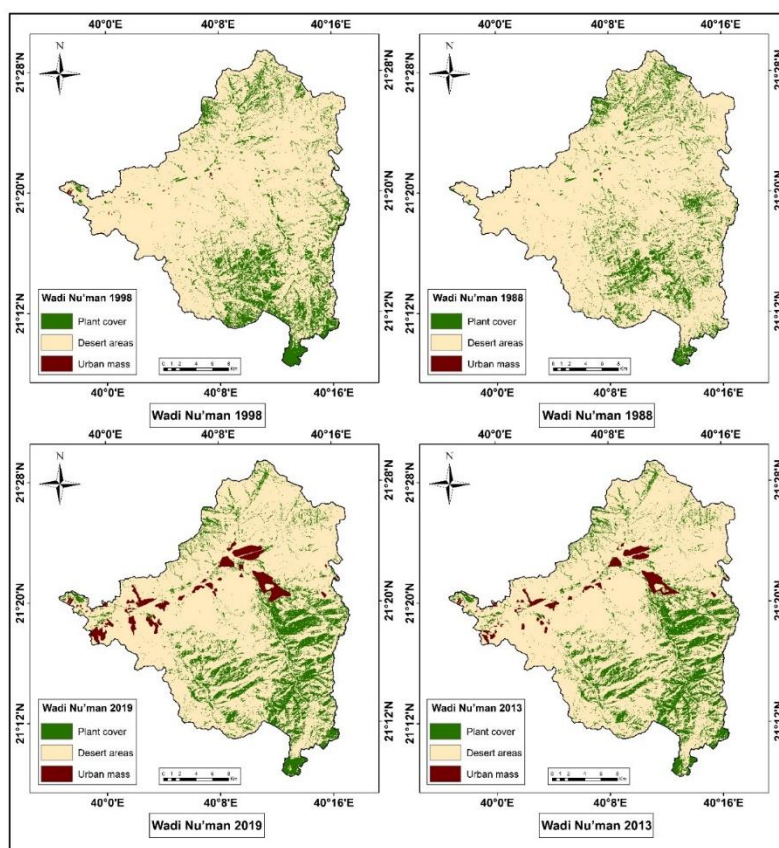


Figure 17. Monitoring land use changes of the Wadi Nu'man basin during the period from 1988–2019.

5.1.2. Urban Areas

Over the last century, the urban area of the Wadi Nu'man basin consisted of small, scattered urban areas. Since the beginning of this century, urban expansions have begun in the plains of the main valley and its tributaries, and urban communities, as well as future urban schemes, have begun to emerge in the form of residential areas and commercial schemes, some of which are slum areas and others are planned areas.

In 1988, the area of urban units reached about 0.53 km^2 , which spread in the plain areas of the main Wadi Nu'man, constituting about 0.08% of the total area of the Wadi Nu'man basin. This percentage multiplied in 1998, where the area of scattered urban units reached about 1 km^2 , representing about 0.15% of the total area of the Wadi Nu'man basin, with an increase of 88.7%, compared with the area of urban units in 1988. Then, there was an excessive increase in the area of the urban areas in 2013. The area of the urban areas and the new plans reached about 17.28 km^2 in 2013. These areas occupied different parts in the plain areas of the main Wadi Nu'man and its tributaries, accounting for 2.51% of the total area of the Wadi Nu'man basin, with an increase of 1600%, compared with the area of urban units in 1988. This excessive increase is due to the establishment of complete urban communities and schemes. These expansions and urban schemes increased until 2019, when the area of urban areas and schemes reached about 26.9 km^2 , constituting about 3.91% of the total area of the Wadi Nu'man basin, as evidenced by the fact that the annual growth rate during the period from 1988–2019, was about 13.06%. This shows that the average annual increase during the same period reached 1 km^2 .

5.1.3. Desert Areas

The area of the Wadi Nu'man basin was originally a desert area, covered by scattered, impoverished trees and plants. In 1988, the barren desert areas and desert areas with scattered sparse vegetation reached about 599.9 km^2 , representing most of the area of the Wadi Nu'man basin and constituting

about 87.19% of the total area of the basin. This area shrank during the period from 1988 to 2019 due to the reclamation of agricultural areas in the plains of Wadi Nu'man and its tributaries, in addition to the construction of many communities and urban schemes. These areas reached about 579.6 km² in 1998, accounting for 84.24% of the total area of the Wadi Nu'man basin, with a decrease of 3.38%, compared with the situation in 1988. It continued to decrease, until it reached 541.76 km² in 2013, accounting for 78.74% of the total area of the Wadi Nu'man basin, with a decrease of 6.53%, compared with the situation in 1998. In 2019, the area of these desert areas reached about 531.11 km², representing 77.19% of the total area of the Wadi Nu'man basin. This shows that the annual growth rate reached −0.38% during the period from 1988–2019, and the average annual increase reached −2.15 km² during the same period.

5.2. Characteristics of the Wadi Nu'man Flooding (Velocity m/s; Depth M; Risk m³/s) and Verification of the Flood Risk Model

Floods in urban areas have been and will continue to be a major problem in many cities in developed as well as developing countries. In order to reduce the impact of these floods, it is necessary to formulate an appropriate flood management policy, which is driven by the knowledge of the frequency and magnitude of the impacts of these floods. Flood risk maps can be used, as an effective tool for water resources and urban planning, by design engineers to assess the vulnerability of the infrastructure and population of this region to the floods [54].

Flood risk mapping and risk analysis of any of the drainage basins involves several factors or criteria [55,56]. The geographic information system (GIS) and remote sensing (RS) have contributed significantly to the analysis of natural hazards [57,58]. Over the past few decades, researchers have been involved in developing different methods and models for natural hazard mapping using RS and GIS technologies [59,60], such as the frequency [61,62], analytical hierarchy [63], fuzzy logic [64], logistic regression [65], artificial neural networks [66–68], evidence weights [69], multi-standard resolution [70,71], and hydraulic modeling, which is an essential tool for flood risk management and mitigation [33,72–77].

The first step in managing urban areas that are prone to flood risk is to prepare a risk map of the floods. Referring to the literature on the modelling of flood risks in urban areas, it was found that the risk matrix method, which is based on the development of a two-dimensional model of the depth, velocity, and spread of water using the hydraulic model (HEC-RAS), is one of the most prevalent methods in the scientific and engineering communities in flood risk assessment, as it provides a two-dimensional environment, and that is what risk modelling in urban areas requires [29]. The risk matrix presents the spatial extent of potential floods in different scenarios. It can be used either in quantitative or qualitative methods. Risk assessment is the identification of a potential risk that may occur at a specified time in the future, along with the determination of its severity and impact. The most important characteristic of this method is its suitability for urban areas. Maps of the water depth, velocity, and levels and flood severity were created. In order to use the model, details of the cross sections of the valley streams and the flow rate at the spring of the streams should be available (m³/s) [34]. Using the conservation of energy formula, the velocity and depth of the water can be calculated [78]. Many previous studies demonstrated that these models have yielded accurate and effective results in flood studies [79,80]. Figure 18 illustrates the classification of risks to humans using a risk assessment (HR). Table 8 shows the risk map classification based on the risk assessment (HR), and Table 9 shows the illustrated risk levels of floods based on the HEC-RAS program, which depends on the velocity and depth of the water. The risk equation is measured in the following equation:

$$HR = d(v + 0.5) + DF$$

where:

HR: Risk rate.

d: Flood water depth (m)

v: Flood velocity (M/w).

DF: A coefficient that takes sediments into account, and its value is assumed to be:

5.0 for depths lesser than 25.0 m; and

0.1 for depths greater than or equal to 25.0 m.

Risk Matrix					Overall Flood Risk	
Likelihood ↑	High				High	
	Medium				Medium	
	Low				Low	
	Very Low				Very Low	
		Minimal	Minor	Significant	Severe	
Potential Impacts →						

Figure 18. Human hazard classification using a hazard assessment (HR).

Table 8. Flood intensity levels.

Levels of Sever Flood	Maximum Water Depth (m)		Maximum Water Outcomes (h) with the Highest Velocity V (m ² /s)
High	H > 1.5 m	or	vh > 1.5 m ² /s
Moderate	0.54 m < h < 1.5 m	or	0.5 < vh < 1.5 m ² /s
Low	0.1 m < h < 0.5 m	and	0.1 m ² /s < vh < 0.5 m ² /s

Table 9. Hazard classification using a hazard assessment (HR).

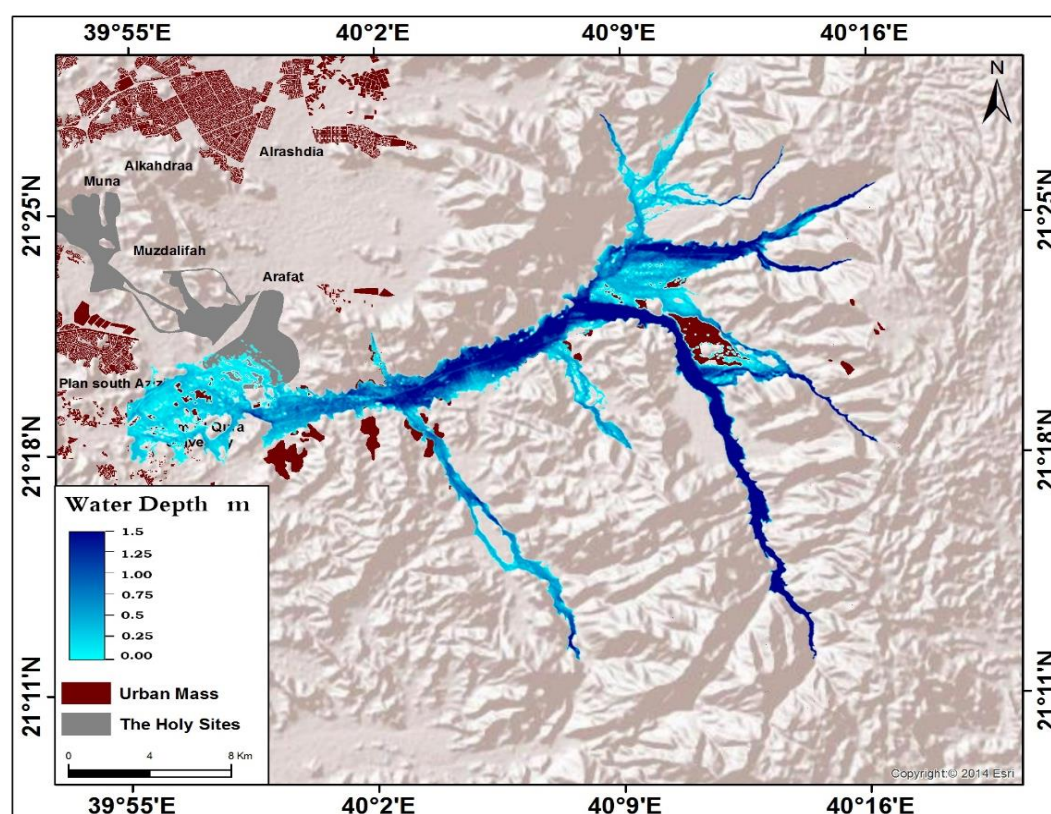
Risk Rate	Risk Categories Impacting Humans	Color Symbol
Less than 0.75	Very low risk	
0.75:1.25	Risk for some ages, including children and the elderly	
1.25:2.00	Risk for the majority of people, including the whole population	
More than 2:00	Risk for all, including emergency cases	

The analysis, shown in Table 10 and Figures 19–22, as well as field studies of the calibration and verification of flood scenarios that occurred in the city on 3 November 2018, showed that the high-depth category (3.5 upwards) represented about 45%, constituting about 15.67 km². These areas are concentrated in the eastern and southern parts of Wadi Nu'man, particularly in the urban communities of Al-Lasqa, Al-'alia, and Al-'argaa. The high-velocity category (3.5 upwards), on the other hand, represents about 50% and constitutes about 74.61 km². These areas are concentrated in the eastern and south-eastern parts of Wadi Nu'man, particularly in the urban communities of Al-Lasqa, Al-'alia, and Al-'argaa.

Historical flooding events were used in the verification sites (VP1–VP3) for the outputs from the flood risk analysis, constructed in the 2-D modeling using the hydraulic modelling program (HEC). The verification results were incorporated into a risk map, and Figure 21 shows the latest floods in the region on 3 November 2018, registered by the satellites, and also used the study to verify the validity of the models. Considering all of the estimates of experts and comparing them with the results of the model, the study could not use results similar to those for neighboring basins, where the study area and most of the dry valleys suffer from a lack of measurements of torrents and floods. Perhaps only one case of real measurements was detected for the rainstorm floods on 13 February 2010, which reached 55 mm in the basin of Wadi Garnha, adjacent to the basin of Wadi Nu'man, which resulted in high torrents that reached a peak discharge of 431 m³/s [81].

Table 10. Characteristics of the Wadi Nu'man flooding (depths (m); speed (m/s); risk (m^3/s)).

Severity	0–1.5 (Low)	1.5–3.5 (Moderate)	More Than 3.5 (High)	Total
Characteristics of the Nu'man valley (depth "m")	22.38	59.68	67.15	149.21
%	15	40	45	100
Characteristics of the Nu'man valley (velocity "m/s")	22.38	52.22	74.61	149.21
%	15	35	50	100
Characteristics of the Nu'man valley (Hazard " m^3/s ")	29.84	52.22	67.15	149.21
%	20	35	45	100

**Figure 19.** Map of the depth of the flood of Wadi Nu'man in 2019.

The checkpoints of the points, VP1–VP3, assembled in front of the university of Umm Al-Qura, indicated that the water level rose by 3.5–4 m, the water speed was 1–1.5 m/s, and estimates of the peak discharge ranged between 640–680 m^3/s . These points were obtained from the database of the hydrological consultancy study for the construction of a dam and the university of Umm Al-Qura, under the supervision of the Faculty of Engineering at the university of Umm Al-Qura. Most of the results obtained from this verification indicate the reliability of the hydrological and hydraulic model that was built in this study, based on the hydraulic and hydrological modelling.

The results of the simulation were also found to be closer to the real situation. The high-risk hazards (5.3 upwards) represented about 45%, constituting about 15.67 km^2 of the areas exposed to the flooding of Wadi Nu'man. These areas are concentrated in the eastern and south-eastern parts of Wadi Nu'man, particularly in the urban communities of Al-Lasqa, Al-'alia, and Al-'argaa.

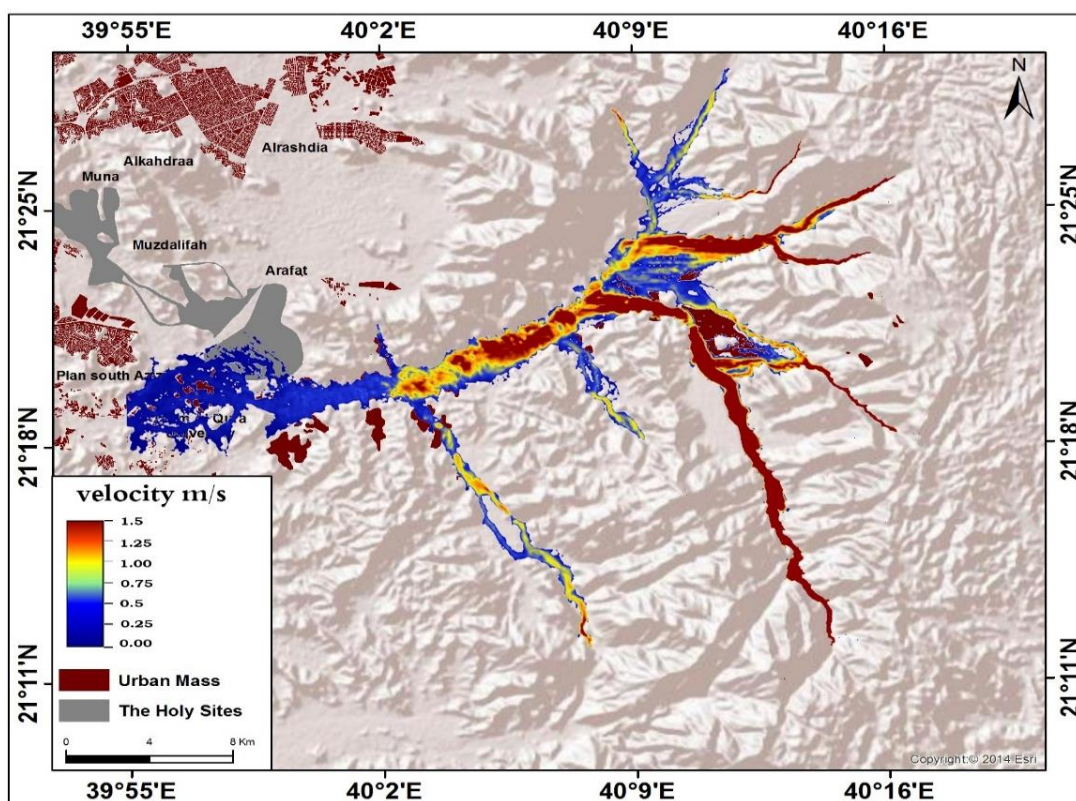


Figure 20. Map of the velocity of the floodwater of Wadi Nu'man in 2019.

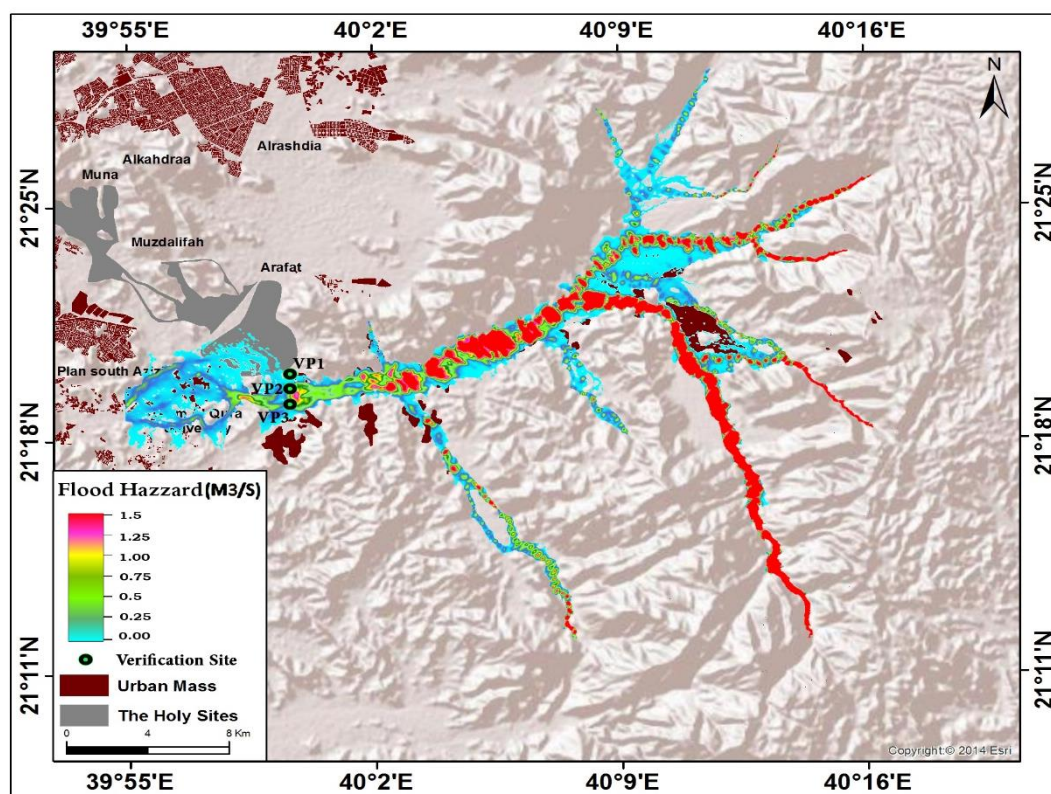


Figure 21. Verification of the flood risk model. Areas prone to inundation and the classification of the degrees of risk in Wadi Nu'man in 2019 are shown.



Figure 22. Part of the field study in the area under study on 3 November 2018. (a) The impact of the Wadi Nu'man flooding; and (b,c) the urban and agricultural areas of Wadi Nu'man.

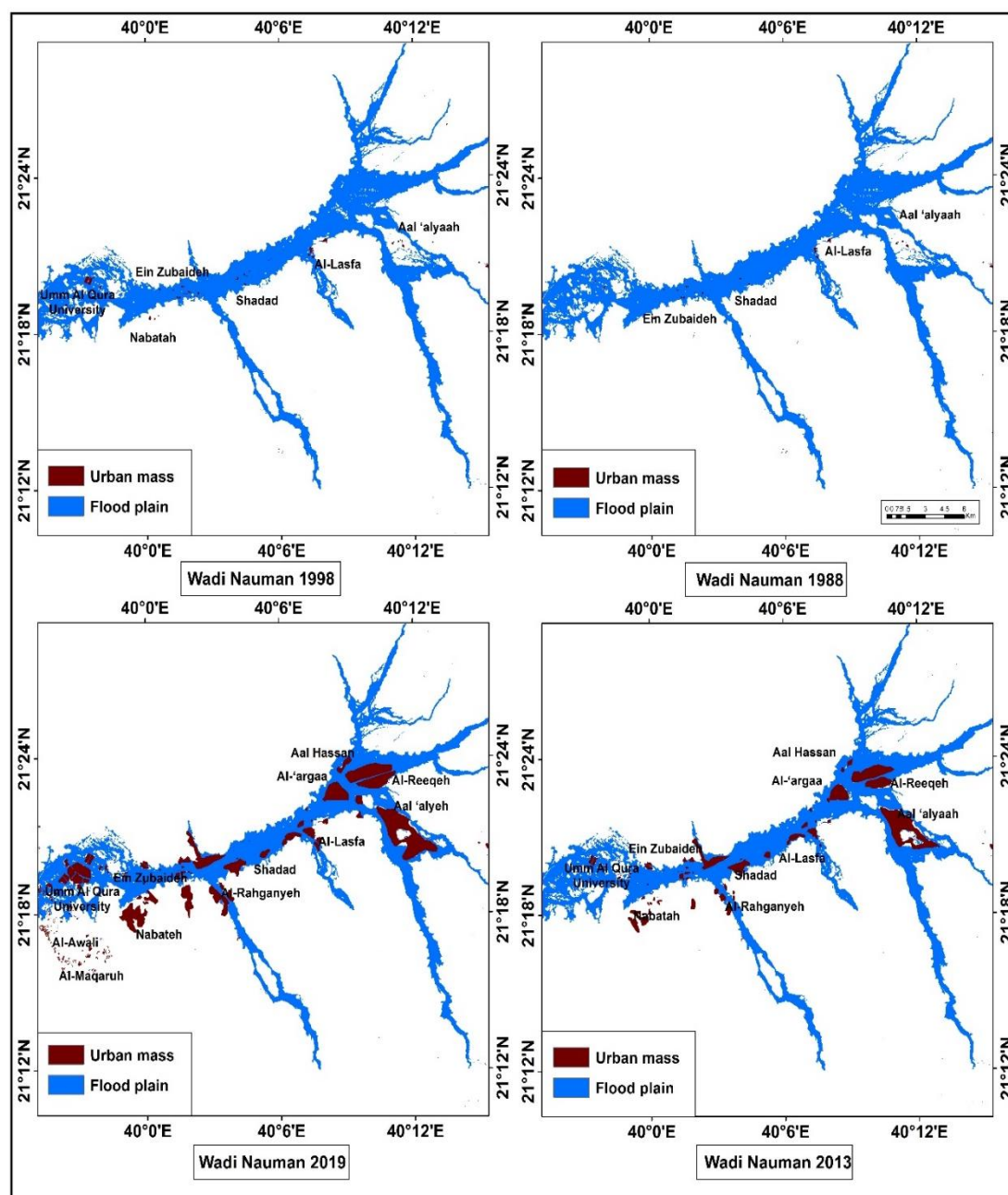
The mid-risk hazards ($1.5\text{--}3.5\text{ m}^3/\text{s}$), on the other hand, constituted about 35% and represented about 52.22 km^2 of the areas exposed to the flooding of Wadi Nu'man. These areas are concentrated in the north-eastern parts of Wadi Nu'man, particularly in the urban communities of Al-Shathqaa and Rin. The low-risk hazards ($0\text{--}1.5\text{ m}^3/\text{s}$) constituted about 20% and represented about 29.84 km^2 of the areas prone to the flooding of Wadi Nu'man. These areas are concentrated heavily in the western parts of Wadi Nu'man, particularly in Al-Masha'er Al-Muqadasa, Umm Al-Qura university, and the Al-'awali district. This requires decisive intervention by those involved in urban environment management and planning in the city of Mecca. A mechanism must be found to prevent the risk of the flooding of Wadi Nu'man threatening Al-Masha'er Al-Muqadasa.

5.3. Urban Areas Prone to Flooding in the Wadi Nu'man Basin during the Period from 1988–2019

Four phases were analyzed in order to arrive at the urban changes and the sub-basins affected by the flood hazards. Data analysis showed an increase in the areas prone to flood risk during the period from 1988–2019, which is approximately 25 times higher than the areas prone to flood risk in 1988 (from 0.53 km^2 to approximately 26.4 km^2). The increase of urban areas prone to flood reached approximately 26.4 km^2 , and this increase was spread over a period of thirty-one years, with a growth rate of 13.06% and an average annual increase of 1 km^2 . The period from 1998–2013, had the highest increase in the areas prone to the flood risk, as the annual growth rate of this period reached 20.92% (Table 11). Figure 23 illustrates the relationship between the flood risk of Wadi Nu'man and the urban development during the period from 1988–2019.

Table 11. Urban areas exposed to flooding in the Wadi Nu'man basin in the period from 1988–2019.

Growth Period	Area (km ²)	Total Increase		From Year 1988 %	Average Annual Increase (km ²)	Annual Growth Rate %	Change Rate 1988–2019 %
		km ²	%				
1988	0.53						
1998	1	0.5	1.75%	88.68%	0.05	6.55%	88.68%
2013	17.28	16.3	60.52%	3071.70%	1	20.93%	1628.0%
2019	26.9	9.6	34.76%	1815.09%	2	7.66%	55.67%
1988–2019		26.4	98.03%	4975.47%	1	13.51%	98.03%

**Figure 23.** The relationship between urbanization and the increased risk of flooding of the Wadi Nu'man basin during the period from 1988–2019.

Urban areas exposed to flooding reached about 0.53 km² in 1988. These areas were affected by the 'alq, Nu'man, and 'ar'ar valleys. The most important urban communities that were affected by flooding in that period were: Al-Lasfa, Aal 'alyaah, Shadad, and Ein Zubaideh. The urban areas exposed to flooding in 1998 reached about 1 km², and these areas were affected by the 'alq, Nu'man, 'ar'ar, and Rehgan valleys. The most important urban communities that were affected by the flooding of these valleys in that period were: Al-Lasfa, Aal 'alyaah, Shadad, Ein Zubaideh, and Nabatah. As for the year 2013, urban areas prone to floods reached 17.28 km², and these areas were affected by the 'alq, Nu'man, 'ar'ar, and Rehgan valleys. The most important urban communities that were affected by the flooding of these valleys in that period were: Ein Zubaideh, Al-Rahganyeh, Shadad, Al-Lasfa, Al-'argaa, Aal Hassan, Nabatah, and Al-Reeqeh. In 2019, the areas exposed to flooding reached about 26.9 km², and these areas were affected by the 'alq, Nu'man, Ya'rug, Rehgan, and 'ar'ar valleys. The most important urban communities that were affected by the flooding of these valleys in that period were: Ein Zubaideh, Nabatah, Al-Rahganyeh, Al-Reeqeh, Shadad, Al-Lasfa, Al-'argaa, Aal Hassan, and Aal 'alyeh.

5.4. Environmental Impacts of Flooding in the Wadi Nu'man Area

The delineation and classification of flood prone areas of the Wadi Nu'man area reveal that an area of about 37 km² is affected by the floods. The geographical distribution of flood intensity zones are in the western and southern parts of the study area, with pivotal land uses, so these areas are subjected to destructive floods and environmental hazards, such as flood risks, and most of the infrastructure is located in the lower section of Wadi Nu'man.

The socio-economic problems of the study area exposed to the flood risk are crop damage, demolished buildings, and destroyed structures in the Al-Mash'ar area, affecting more than a million lives, according to the Hag times.

A lot of debris flow is caused by a combination of factors, which are particular to the area, and result in damage to the human life and property in the form of deposition, entrainment, or direct impact [82].

The chemical properties of groundwater were affected by the floodwaters of Wadi Nu'man, and some studies show that the average concentration of TDS, Mg, Na, Cl, NO₃, and EC decreased significantly after the floods. The major water types indicate that the infiltration of the surface water has a great influence on the groundwater chemistry.

5.5. Suggested Measures and Protection Procedures against the Floods of Wadi Nu'man

Al-Masha'er Al-Muqadasa, Umm Al-Qura university, and many modern housing schemes are exposed to the floods of Wadi Nu'man, which are accompanied by large amounts of water and sediment, occurring over a short period of time. The existence of insufficient protection against this water may lead to enormous economic losses, the loss of many lives and a significant loss of property. On the other hand, the unstudied urban development of the top of the valley negatively affects the movement of the floodwater and sediment and increases the amount of loss; additionally, it leads to the formation of a slum area, filled with stones and dust around the divergence dam or the berm of Umm Al-Qura university, which led to the narrowing of the flood streams, increasing the velocity of the flow and raising the water level in front of the dam (Figure 24).

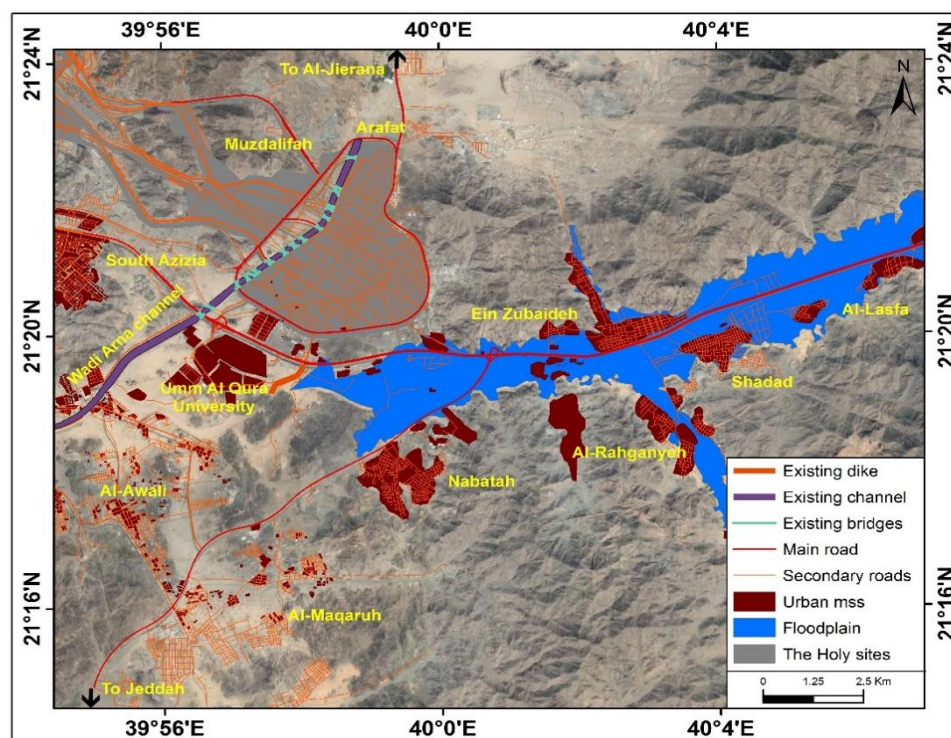


Figure 24. The floodplain of the Wadi Nu'man's flooding and the status quo of the hydraulic facilities in the study area in 2019.

This is a serious issue that requires that the responsible authorities in the Infringements Committee of Mecca governorate and the municipality of the Holy Capital remove the encroachments in order to reduce the seriousness of potential disasters caused by great floods. This requires the establishment of hydraulic facilities in order to control, obstruct, and divert floods to prevent these hazards and protect people's lives and property.

The designed drainage of a 100-year flood, based on the hydrological study of Wadi Nu'man, reached about $82.2689 \text{ m}^3/\text{s}$. Consequently, the study suggests establishing a six-m high dam and developing an area, located in front of the diversion dam, while maintaining a channel with a width of 200 m and immediately expanding the channel in the part behind the dam (the controlling part) to a width of 200 m.

The forces affecting the dam, multiplied by the width of the stream of Wadi Nu'man's water supply, equaled 200 m. The results of the analysis revealed that the height of the flood water will not exceed the height of the dam (5.7 m). The results also showed that the static forces reached 16 T/m and that the dynamic forces that resulted from the water's velocity in a stream with a width of 200 m reached about 9.1 t/m. In any case, this local protection must be secured by a group of dams and lakes on the main branches of Wadi Nu'man, working on the fragmenting and dispersing of the flood water, before its catchment, to reduce the amount and the drainage of the water that reaches the site of the university and Al-Masha'er Al-Muqadasa (the southern part of Arafat). There should be a coordination with the concerned authorities, so that there will be no serious impact on the university and Al-Masha'er Al-Muqadasa, and in order for the solution to be complementary and economical.

The purpose of this alternative is to distribute the drainage of Wadi Nu'man to a rectangular channel, south of the dam, in the controlling part, with a width of 200 m. The hydraulic study of this solution showed that the depth of water in front of the dam will be less than 3 m, which means that the dam will not be flooded with water, and the water will not cross into the university, Al-Masha'er Al-Muqadasa of Arafat, or the surrounding residential communities. The southern channel can be expanded in order to reduce the height of water rises and reduce the risks of water for the population and the lands behind the dam. It is necessary to increase the width of the diversion channel of Wadi

Nu'man at the end of the dam to at least 200 m. This requires rock cutting to a distance of 1225 m, and the rock cutting would reach about 2.2 million cubic meters. It is also necessary to refine the slope of the channel of the area to increase the drainage velocity. Figure 25 illustrates the protection measures proposed to prevent the risks associated with the floods of Wadi Nu'man. The proposals and solutions presented in the manuscript were subjected to public discussion and were discussed with decision-makers at the Holy City of Makkah, and they are based on the implementation and planning of the floods. The quantitative impact of these plans on the decision-makers' ability to reduce the flood risk in quantitative terms was also measured.

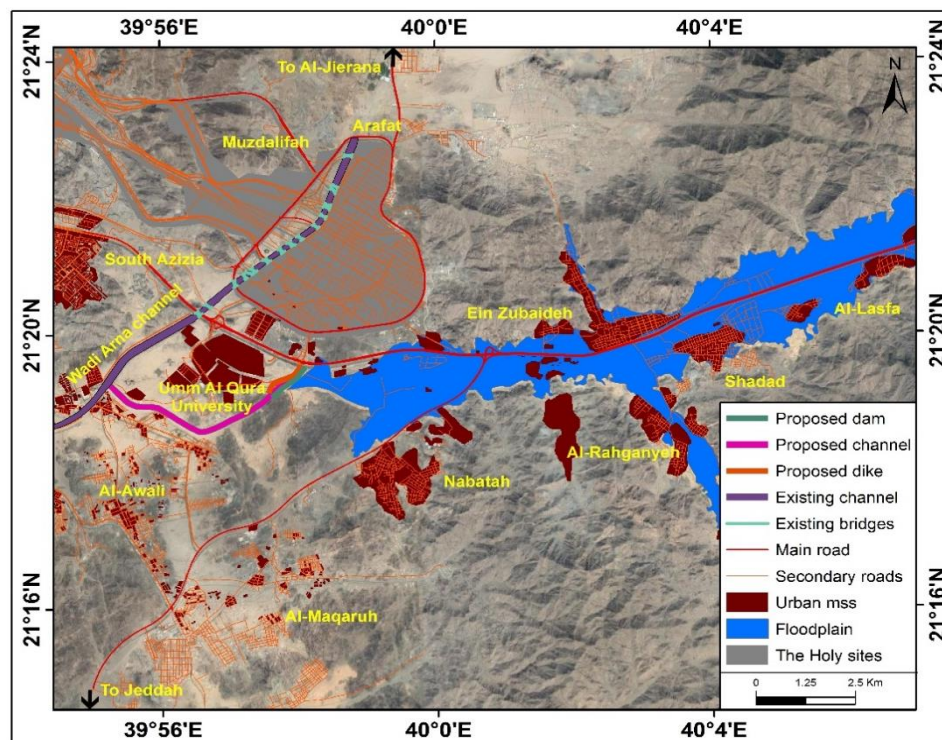


Figure 25. Protection measures, proposed to prevent the dangers of the floods of Wadi Nu'man on Al-Masha'er Al-Muqadasa in 2019.

6. Recommendations

The recommendations made based on this study prioritize the implementation of a plan for the prevention of flood hazards and the protection of infrastructure through the maintenance of existing floodwater drainage facilities, represented by the Wadi 'ernah drainage channel, which lies to the west of Umm Al-Qura university and Al-Masha'er Al-Muqadasa of Arafat. This channel is of great importance due to its integration with the channel proposed in this study. The result of this study highlights the necessity of establishing hydraulic facilities for the control, obstruction, and divergence of the floods of Wadi Nu'man, and the specific recommendations are as follows:

- The construction of a dam with a height of six m and the development of the area, located in front of the divergence dam, in addition to maintaining a channel with a width of 200 m and widening the channel in the part lying immediately after the end of the dam (the controlling part) to 200 m.
- Increasing the width of the diversion channel of Wadi Nu'man, which is located at the end of the diversion dam, to a width of at least 200 m. This requires rock cutting to 1225 m, and the rock cutting would reach about 2.2 million cubic meters. It is also necessary to refine the slope of the channel of the area to increase the drainage velocity.
- Increasing the height of the alluvial barrier, established to protect the southern side of the university, as well as the residential neighborhoods to the south of the university.

- The protection of the western side of the university residence by placing an alluvial barrier, with a height of at least two m, along Wadi 'erneh.
- If urban development is allowed in the area located in Wadi Nu'man, to the east of the university residence, there must be a canal for the drainage of the valley's floods, with a width of at least 200 m and a depth of 4.5 m.
- The prevention of building in the streams of valleys and areas of flood catchment by assigning a reserve for each stream, which should not be infringed upon by the removal of the current encroachments. Moreover, there must be a mandatory study of the risks of floods, as well as their apex and catchments, provided with each project and submitted to the competent authorities for building permission.
- The adoption of a plan to harvest water at the top of the sub-valleys of Wadi Nu'man, which would help greatly in providing people and farms with water. It would also help in afforestation, which slows down the floods and enables them to feed the underground reservoirs. At the same time, it would decrease part of the wasting floods towards the danger zone in the lowest part of the Wadi Nu'man basin. It should be included in projects that prevent flood risks, focusing on, e.g., drainage channels, barriers, canals, dams, water catchments, water harvesting, etc., in the upper or middle sectors of the valleys, but not in the periphery of the flood-targeted areas.

7. Conclusions

Al Masha'er Al Muqadasa, Umm Al-Qura university and many modern housing schemes are frequently exposed to the floods of Wadi Nu'man, whose drainage apex approximately reached $2689.82 \text{ m}^3/\text{s}$ during a return period of 100 years. During the time period from 1988–2019, the urban areas exposed to flooding increased by approximately 25 times since the year 1988 (from 0.53 km^2 to 26.9 km^2). This increase is distributed over thirty-one years, with a growth rate of 13.06% and an average annual increase of 1 km^2 . The high-risk category (3.5 upwards) dominates up to 45%, constituting about 67.15 km^2 of the areas prone to the Wadi Nu'man flooding. The medium-risk areas ($1.5\text{--}3.5 \text{ m}^3/\text{s}$) constitute 35%, representing about 52.22 km^2 of the areas prone to flooding. The low-risk category ($0\text{--}1.5 \text{ m}^3/\text{s}$) constitutes about 20% and represents about 29.84 km^2 of the areas prone to flooding. The study showed that what contributed to the increase of the risk of floods in the area under study are the following: The adoption of urban plans, without considering the paths and tributaries of the valleys; constant landfilling, caused by the inhabitants and service developers, without a clear mechanism that prevents the dangers of floods on Al-Masha'er Al-Muqadasa; and the formation of a slum area filled with stones and dust around the diversion barrier of Umm Al-Qura university, which led to the narrowing of the flood streams, as well as an increase in the velocity of the flow, thus raising the level of the water. This requires a decisive intervention by those involved in the management and planning of the urban environment in the city of Mecca. A mechanism that prevents the dangers associated with the floods of Wadi Nu'man for Al-Masha'er Al-Muqadasa.

Therefore, the protection alternatives proposed in this study to prevent flood risks are realistic and in line with the kingdom's 2030 plan and vision. They are as follows: The implementation of a range of new hydraulic facilities, integrated with the existing hydraulic ones via the construction of a six-m high dam, and the development of the area located before the divergence dam, while maintaining a channel with a width of 200 m and expanding the channel in the place immediately after the end of the dam (the controlling part) to a width of 200 m. These alternatives aim at distributing the drainage of Wadi Nu'man to a rectangular channel, south of the dam, which originates in the controlling part, with a width of 200 m. The hydraulic study of this solution showed that the depth of water in front of the dam would be less than 3 m, which means that the dam would not get flooded and that the flood would not reach the university, Al-Masha'er Al-Muqadasa of Arafat, or the surrounding residential communities. The southern channel could be expanded to reduce the water's height, as well as the resultant risks that would threaten the population and the land behind the dam. Moreover, it is necessary to increase the width of the diversion channel of Wadi Nu'man to a width of at least 200 m.

Author Contributions: A.A.K. and A.F.D.G. designed the study, collected and analyzed the data, developed the research idea and planned the research activities, carried out the research, including collecting the input data and prepared manuscript, and carried out a statistical analysis of the obtained results., and interpreted the datas , upervised the research activities and reviewed the final draft of the manuscript, A.A.K.wrote the manuscript, provided valuable comments in writing this paper, and professionally edited the manuscript. All authors have read and approved the final manuscript.

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