Hydraulic Simulation of Flash Flood Hazard on the Urban Road Network in the Wadi Ibrahim Basin in the Holy City of Mecca: A Geographic Study

المحاكاة الهيدروليكية لمخاطر السيول على شبكة الطرق الحضرية في حوض وادي إبراهيم بمدينة مكة المكرمة دراسة جغرافية

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Abstract

This study comes due to the importance of the role of urban transportation within the city of Mecca, as it is considered one of the important and changing pillars that affect the city. This is due to the increasing population and urban growth and the attempt to achieve an appropriate level of service and safety. This research discussed the application of hydraulic simulation of flow on the urban road network during rainstorms in the Wadi Ibrahim Basin in the city of Mecca. This study relied on geographic information systems in the preparation of spatial data, including the urban road network, extracting the values of the water flow curve (CN), and determining rainstorms designed for return periods of 100 years depending on the weather monitoring station for the city of Mecca. The study reached the determination of the volume of torrent water (m^3), water depth (cm), water concentration time in the basin (hours) and water speed (m/s), as well as the preparation of the torrent hydrograph and the rain intensity curve. The results showed an increased risk of sudden torrential rains on the road network and streets surrounding the buildings in the direction of the mainstream of the Wadi Ibrahim Basin. With the help of hydraulic simulation through the HEC-RAS software program, the volume of water flow and the flow simulation on road networks and streets surrounding buildings were predicted, as well as the sites that may affected by the risk of flash floods were identified. Solutions were developed by

identifying points at risk, where they were classified into four categories: low, medium, high, and very high risk. Current flood drainage network projects were also reviewed and studied. This work helps planners and decision-makers follow the necessary methods to protect urban areas from the possible risk of potential flash floods. This could be before, during and after the occurrence of the event.

Keywords:

Urban Road Network - Hydraulic Simulation – Flash Flood Drainage Networks – Rainstorms - Mecca – Saudi Arabia

Introduction

The analysis of flash flood hazards using hydraulic simulation plays a crucial role in examining the urban road network in the city of Mecca. For example, on April 15, 2020 (Ministry of Water and Electricity, 2020), heavy thunderstorms led to rainfall of up to 172 mm within a short period that did not exceed 3.21 hours in a small and steep drainage basin. The basin area did not exceed 97 km^2, which caused the generation of a high flow of about 14.5 million m^3. The observed water depths in some water pools in the urban road network reached about 1.50 m, accompanied by high speeds carrying a lot of cars and rubble, which caused serious damage to buildings and property and disrupted traffic.

Studies of flash floods in urban areas still need more technical applications. Studies on this subject are limited, hampering a comprehensive understanding of this phenomenon. On the studied area, Abdul Razzaq (1993) presented a research study for King Abdulaziz City for Science and Technology in Riyadh "Evaluation of the quantities of torrents and their effects in the southwest of the Kingdom" that aimed to know the characteristics of the flow of torrents and predict their quantities and frequency, with the application to Wadi Atoud. Another study by Sami bin Ati (2003) entitled "A Proposed program to educate citizens about the dangers of floods - a case study - Wadi Al-Leith in Mecca Al-Mukarramah region". A third study by Al-Tuwairqi (2003) presented a proposed program to educate citizens about flood hazards by applying to Wadi Al-Laith in Mecca Al-Mukarramah region at the Naif Arab Academy for Security Sciences. Al-Zahrani's (2007) study dealt with the impact of flood risks on the safety of pilgrims in Mina-Mecca. Borouba (2007) presented a hydromorphometric study to estimate the size of the Wadi Atoud basin floods in Saudi Arabia. It also dealt with the assessment of the flood hazard in the Wadi Al-Numan basin, southeast of Mecca Al-Mukarramah, where this study relied on the integration of geomatics and hydrological modeling (Ahmed et al., 2019; Othman et al., 2020), as well as the use of integrated hydrological modeling of water runoff in assessing the risk of floods in the east of the city of Mecca Al-Mukarramah (Mina Hair).

At the global level, Mason et al. (2009) and Shaaban et al. (2020) examined flood risk assessment using remote sensing and GIS techniques based on hydrological characteristics and multi-criteria statistical decisions. Chen et al. (2009) and Fox et al. (2012) applied geometric applications to estimate the effects of flash flood hazards on urban areas in relation to land-use changes. Studies by Rawat et al. (2013) and Attwa et al. (2021) were concerned about the impact of floods on urban urbanization and the impact of land use change in drainage basins and its relationship to torrential flows. Siddayao et al. (2014) studied the geomatics integration and mathematical hydrological modeling for spatial analysis of urban areas' vulnerability to flash flood hazards and mitigation of the likelihood of damage. Other studies (e.g., Rawat et al., 2013; El-Saadawy et al., 2020; El Bastawesy et al., 2020) showed the impact of urban encroachment on the natural cover of the land and the resulting significant modifications in the hydrological behavior of the basins.

2. Data and Methods

2.1. Study Area

Wadi Ibrahim is one of the most important valleys affecting the city of Mecca, and is located between 21° 18' 48", 21° 28' 2" north and 39º 56' 12", 39º 47" 18" east, heading from northeast to southwest (Figure 1), with an area of 97 km^2. It includes the central municipalities of the city of Mecca, namely: Al-Maabda, Al-Gaza, Ajyad, Al-Misfala, Al-Shawqia, Al-Shara'a, Holy Sites, Al-Aziziyah, and South of Mecca. It collects its waters from the mountains of Thabeer and Jabal Al-Nour in the northeast of the city of Mecca Al-Mukarramah and extends in a southwesterly direction with a length of about 24 km until it meets Wadi Arna. The city of Mecca Al-Mukarramah is characterized by a distinctive pattern in urban road networks, where urbanization extends radiantly from the central area of the Grand Mosque to the stomachs of the surrounding valleys. These valleys are currently considered internal streets, and this was reflected in the urban fabric where it appears in a section as a result of the mountains that separate the streams of the valleys. However, as a result of the increase in population pressure and the lack of suitable spaces for urban expansion, the urban fabric was connected in some locations, helped by rock-cutting off parts of the mountains and the construction of tunnels to enhance the ease of urban communication of road networks between the city's neighborhoods.

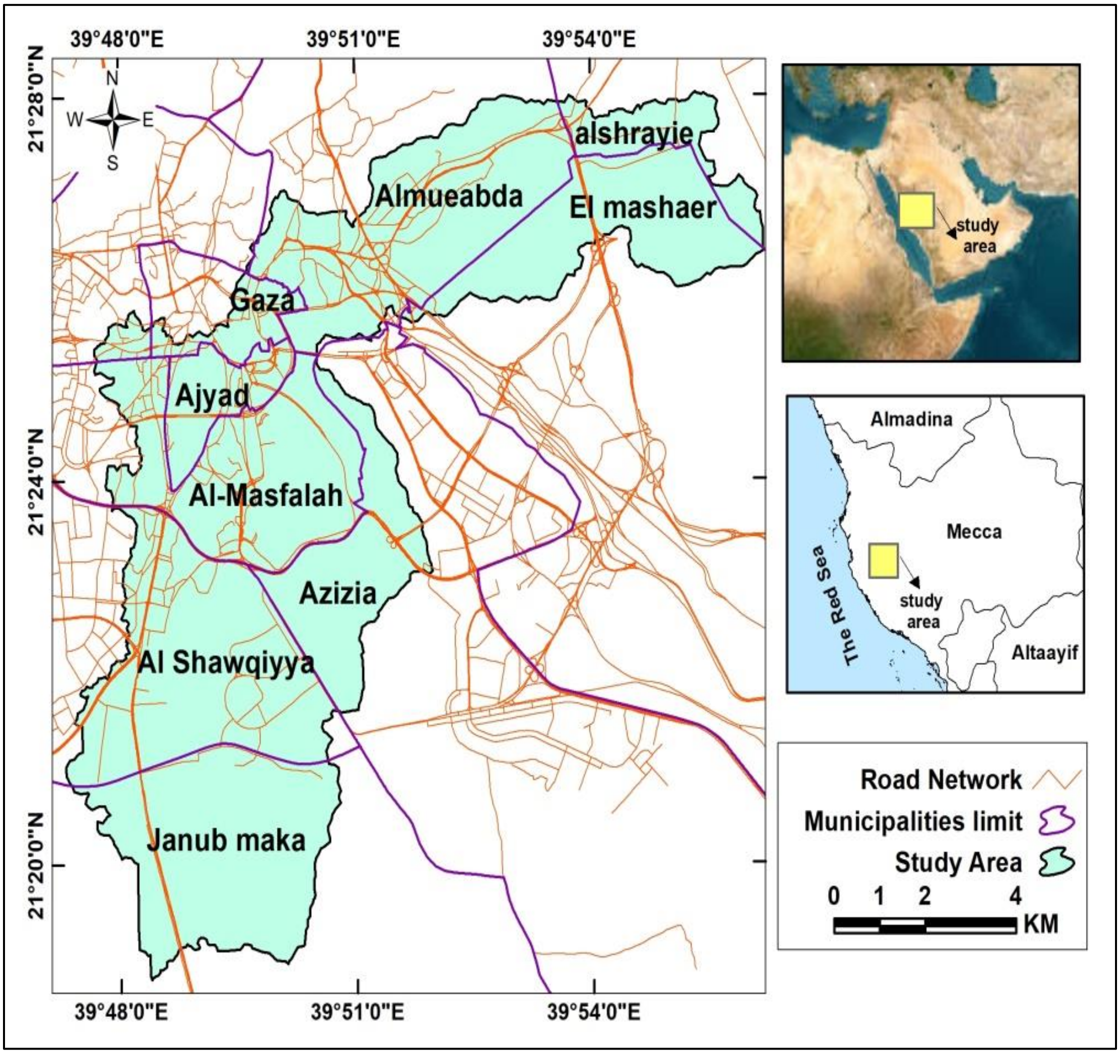


Figure (1): Location map of the studied area.

2.2. Methodology

In light of the sudden rainstorms that the holy capital is exposed to, which cause many spatial problems associated with the flash flood hazards on urban road networks and torrential drainage, this study comes to contribute to the process of managing floods in the Wadi Ibrahim Basin within the city of Mecca, analyzing their characteristics and potential effects, identifying risky sites in road networks and the sensitivity of buildings to the flash flood hazard and developing solutions commensurate with the urban character of the city of Mecca.

The study was carried out in several stages. The data collection stage, in which the Landsat OLI satellite images were obtained from the website of the US Geological Survey (USGS) in 2019, a digital elevation model (DEM) with an accuracy of 12.5 m, and the climatic data from the weather monitoring station for the city of Mecca during the period from 1995 to 2020, as well as the urban road networks of the city of Mecca and the different layers related to the buildings (Figure 2). For the field study phase, field measurements were carried out, some field photographs were taken, as well as observations and field measurements were recorded. Later, during the stage of processing and analyzing the data, engineering correction of maps and satellite images was performed. Additionally, processing, analysis and modeling of data and obtaining final results have been achieved.

To achieve the objectives of the study, the SCS-CN model approved by the American Soil Conservation Curve Number Service SCS-CN was applied to determine the volume of flow, because of the great impact of this factor on the road network, and it is also one of the inputs of hydraulic simulation. One of the most important inputs is the coefficient of the water flow curve number (CN). This model is the most widespread method of estimating runoff in engineering studies and natural resource management projects (USDA-TR55, 1986). Hydraulic simulation data were also prepared to simulate the flow of the torrent during the period of its occurrence on the urban road network in the study area (Table 1).

Table (1): Used formulas in the current study.

No.	Formula	Application	Reference
1.	$QV = (Q \times \frac{A}{1000})$	Flood volume (m^3)	USDA-TR55 (1986)
2.	$Q = \frac{(P - Ia)2}{(P + 0.8S)}$	Run-off depth (mm)	USDA-TR55 (1986)
3.	$S = \frac{(25400)}{(CN)} - 254$	Potential maximum retention after runoff (mm)	USDA-TR55 (1986)
4.	$Ia = 0.2 \times S$	Initial abstraction (mm)	USDA-TR55 (1986)
5.	$TC = 0.057 \frac{L\left(\frac{1000}{CN} - 9\right).7}{\sqrt{J}}$	Time of concentration	George (2009)
6.	VW = L/TC	Water velocity (m^3/s)	George (2009)

Where:

A is the area of the drainage basin, P is the rainfall in mm, L is the length of the basin in km, J is the slope (%), and CN is the curve number.

To apply hydraulic simulation of the scenario of water movement over the road network and surrounding streets, the HEC-RAS software launched by the Center for Hydrological Engineering of the U.S. Army Corps of Hydrological Engineers was used to perform two-dimensional hydraulic simulations. In detail, to simulate the propagation of flood water flows and calculate their hazards on the road network. The two-dimensional hydraulic model was applied in four steps: a) correction or addition of engineering data for cross sections and hydraulic structures, b) input of peak water flow data, c) general definition of the model plan (input files for engineering data are mapped based on the results of hydrological modeling prepared in the previous steps and the introduction of the DEM of 12.5 meters), and finally d) Implementation and verification of hydraulic calculations. The study also relied on some specialized programs that can collect, process, analyze, and model spatial data. More details can be found in Table (2).

Table (2): Software programs used in the current study.

Software	Application
ARCGIS	SCS-CN model data
ERDASE IMAGINE	Processing satellite image data
WMS	Hydrological analysis
HYFRAN	Estimate the probability of maximum rainfall intensity for a given return period
HEC-HMS	Determine the rain intensity curve and plot the torrent hydrograph
HEC- RAS	Hydraulic simulation of torrent flow in the study basin

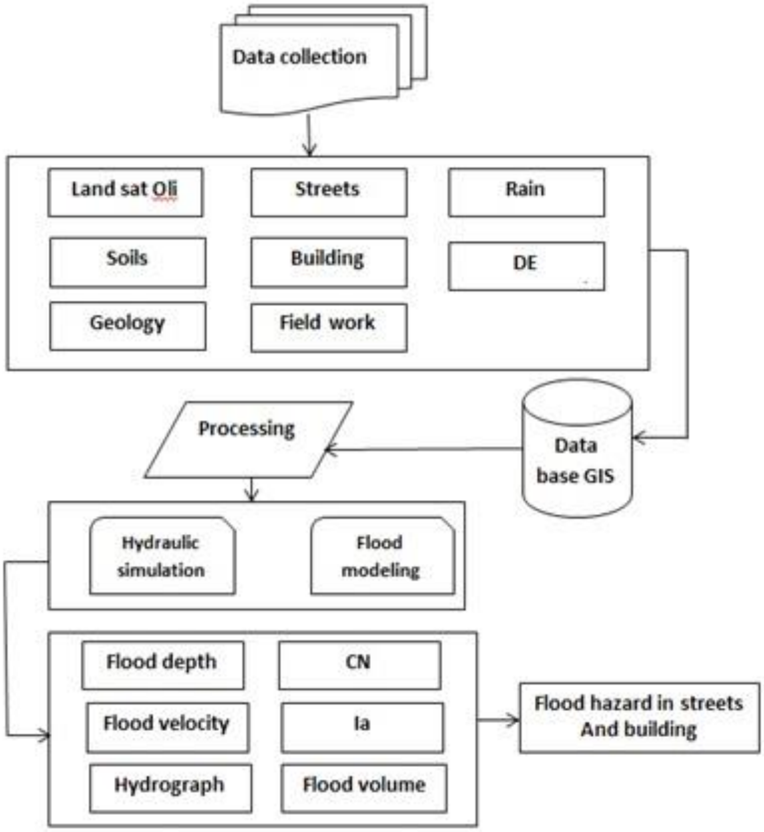


Figure (2): Flowchart shows the methodology for the GIS-based flash flood hazard and risk Assessments in the current study.

2.2.1. GIS Database Collection and Preparation

GIS contributes to accurate and timely decision−making (Awange and Kiema, 2018). The current study relied on a large number of spatial data, foremost of which are: digital maps of road and building networks, sensor data, especially satellite images, and digital elevation models (Table 3), The geographic database also relied on the studied rainstorm climate data and field observation data at the time of the rainstorm. From the analysis of the digital elevation file, the drainage network and topographic maps were derived (Figure 3,4) and it is clear that the Wadi Ibrahim Basin consists of seven ranks.

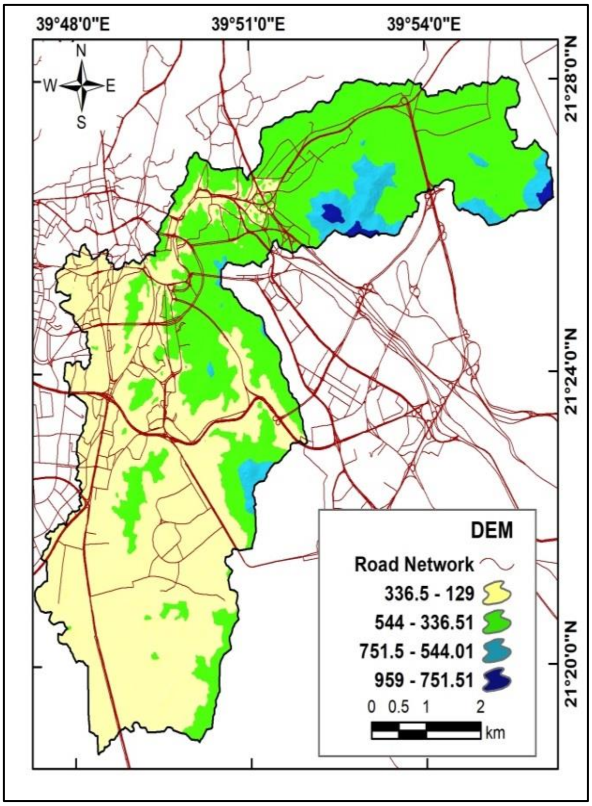


Figure (3): DEM of the study area.

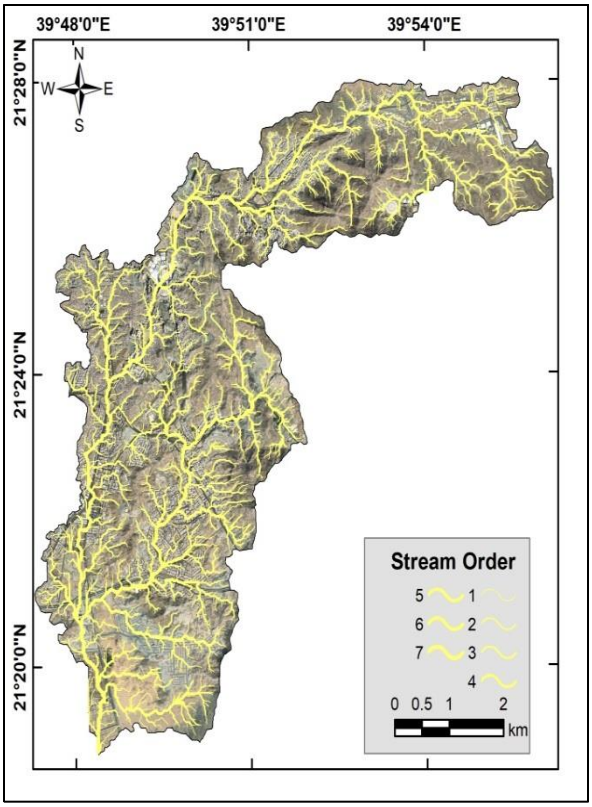


Figure (4): Stream order of Wadi Ibrahim Basin.

Its elevation ranges between 130 to 960 m and is characterized by molting and cutting its surface and it has a varying degree of slope ranging from 7 to 56.38 degrees with an average of 12.7. The study area includes 9 central main municipalities in the city of Mecca, they are: Ajyad, Gaza, Azizia, Shawqia, Misfalah, Maabda, Holy Sites, Sharia and South Mecca (Figure 1), and these neighborhoods are populated and witness high activity in the movement of vehicles, especially in the Hajj and Umrah season as well as visit to the Sacred House of God.

Table (3): Used data in the current study.

No.	Data Type	No.	Data Type
1.	DEM	5.	Fieldwork observations
2.	Satellite images	6.	Climate data
3.	Residential buildings	7.	Topographic maps
4.	Road network map	8.	Field monitoring data

3. Data Analysis

The study relied on employing GIS and remote sensing techniques in the application of hydraulic simulation to study potential flow in the Wadi Ibrahim Basin in the city of Mecca, simulate its impact on the urban road network and streets surrounding buildings, evaluate means of protection from the flash flood hazard and recommend proposals that could contribute to mitigating the possible risk of torrential flow in the study area, as well as identify areas prone to flash floods and develop maps for the sensitivity of the road network and buildings to flash floods, in order to achieve sustainable urban development.

3.1. Rainstorm and Its Characteristics

The accurate determination of the amount of rainfall that falls on the Wadi Ibrahim Basin during the rainstorm is one of the most important factors that help in accurately calculating the size of the torrent, its characteristics and its impact on buildings and the road network. To increase accuracy, the probability of recurrence of rainstorms was calculated in the current work for a return period of 100 years (Table 4).

In this regard, the records for Mecca Al-Mukarramah Rain Station (J114) has been acquired from the available weather stations of the Ministry of Water, Electricity and Environmental Protection.

Table (4): Estimation of potential rainfall amounts for various return periods.

Return Period (years)	100	50	25	20	10	5	3	2
Amount of possible rainfall	172	146	120	112	86.3	60.6	41.6	26.6

Source: analysis of rainfall data from the Makah Al-Mukarramah J114 station, using the exponential method and HYFRAN software.

The choice of the rainstorm with a return period of 100 years due to the reliance of hydrologist experts on this iterative period in the hydraulic design of drainage channels in road networks. Accordingly, the estimated amount of possible rainfall was about 172 mm (Table 4) depending on an exponential statistical method, which favored to increase the accuracy of determining the rainfall during a rainstorm (Figure 5).

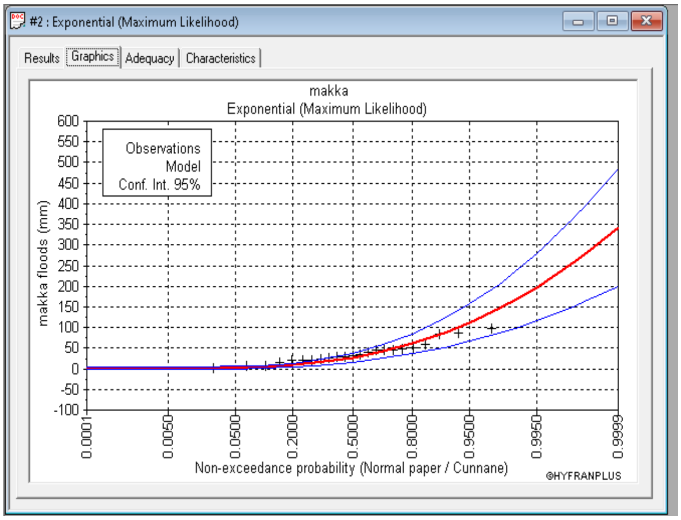


Figure (5): Estimation of a potential rainstorm using the exponential maximum likelihood method.

To identify the characteristics of the rainstorm and its intensity, a rain intensity curve has been prepared, which expresses the relationship between rain intensity and time (Figure 6). It shows that the studied rainstorm changes chronologically in its strength, starting from the zero minute to the 10^{th} minute, where the rainstorm was weak and not widespread, and from the 10^{th} minute to the 20^{th} minute, it intensified, then from the 20^{th} minute to the 30^{th} minute, it spread, and when it reached the 50^{th} minute, it reached its peak.

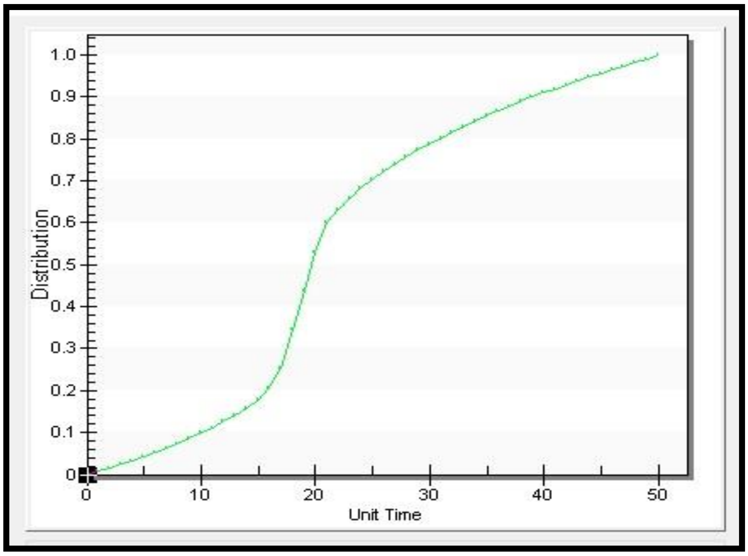


Figure (6): Rainstorm characteristics based on data analysis using HYFRAN PLUS software.

3.2. Estimating the volume of rainfall during a rainstorm

To simulate the water flow resulting from the studied rainstorm and its impact on the road network, the volume of water flow in cubic meters was first determined, until the potential quantity is identified and entered into the hydraulic simulation data, and in that the SCS−CN model was applied, which depends on the classification of land cover and hydrological groups of soil, and their integration together in what is known as the values of the water flow curve (CN Number Curve) (Table 5). The CN values express the hydrology of the soil in terms of its ability to absorb water and range from zero to 100. Whenever the values approach zero means that the surface is permeable to water, but in the case of approaching the number 100, it indicates a low surface permeability to water.

An intermediate value of 50 indicates a kind of balance between runoff rates and water rates (Ponce and Hawkins, 1996).

Table (5): Considered CNS values corresponding to land cover and soil hydrological groups (after USDA, 1986).

Land Cover	Hydrological groups			
	A	B	C	D
Exposed rocks	–	–	–	93
Barren soil	77	86	91	–
Loose rough sediment	76	85	89	–
Roads, asphalt parking lots and building roofs	98	98	98	98
Poor vegetation	63	77	85	88
Well maintained vegetation	55	72	81	86

The inputs of the SCS-CN model have been prepared to estimate the volume of flow based on the weighted water flow curve values (CNs) and the amount of rain resulting from the rainstorm recorded at the Mecca Al-Mukarramah Meteorological Station, and the land cover map. Land cover map includes the following: exposed rocks, barren soil, asphalt roads and parking, as well as buildings and vegetation. The hydrological groups was considered according to the global classification of hydrological soil groups (HSG) and also following Equation (3), where (S) is the potential maximum retention coefficient of soil after runoff, which is also known as the water storage capacity of the soil. This parameter is useful in knowing the maximum capacity of soil water retention after the start of runoff. It was estimated using the thickness of the waterlogged soil, where the values ranged between 13 mm covering an area of 49.44 km^2, and 89 mm with an area of 0.13 km^2, with an average of 41 mm. Therefore, the low values of this coefficient are clearly shown, due to the increase in the construction area and the mountainous slopes with barren soil, and thus the likelihood of high runoff increases as a result of such factors.

According to Equation (4), the initial abstraction coefficient (Ia) was calculated, which expresses water losses through evaporation and leakage from the sites of torrential water catchments before the start of runoff, and their values were close to zero indicating a lack of losses, which helps to generate large amounts of runoff water and vice versa. The coefficient values ranged from 2.6 mm covering an area of 49.44 km^2 to 6.9 with an area of 0.13 km^2. In general, the decrease in the first extraction coefficient in the study basin is evident, as its overall average is 4.18 mm with a standard deviation of 1.7, which indicates an increased likelihood of flash flood hazard during rainstorms.

The runoff depth coefficient (Q) was also calculated according to Equation (2), which expresses the thickness of the residual rainwater. It has the ability to runoff during a rainstorm, and it is clear from Figure (7) that the thickness of the runoff in the basin ranges between 97.77 mm to 137.82 mm, with an average of 149 mm, with a standard deviation of 8.21, which indicates the possibility of severe runoff.

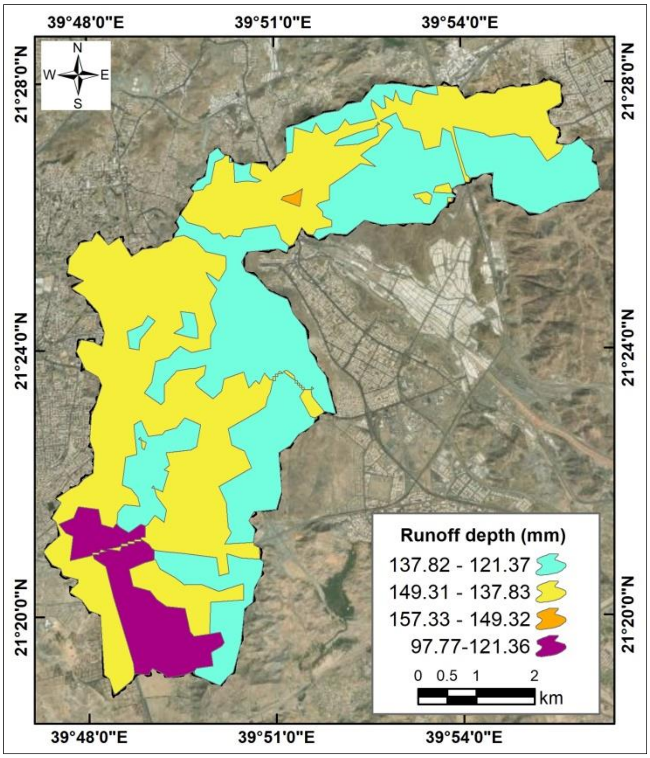


Figure (7): Runoff depth (mm) in the studied area.

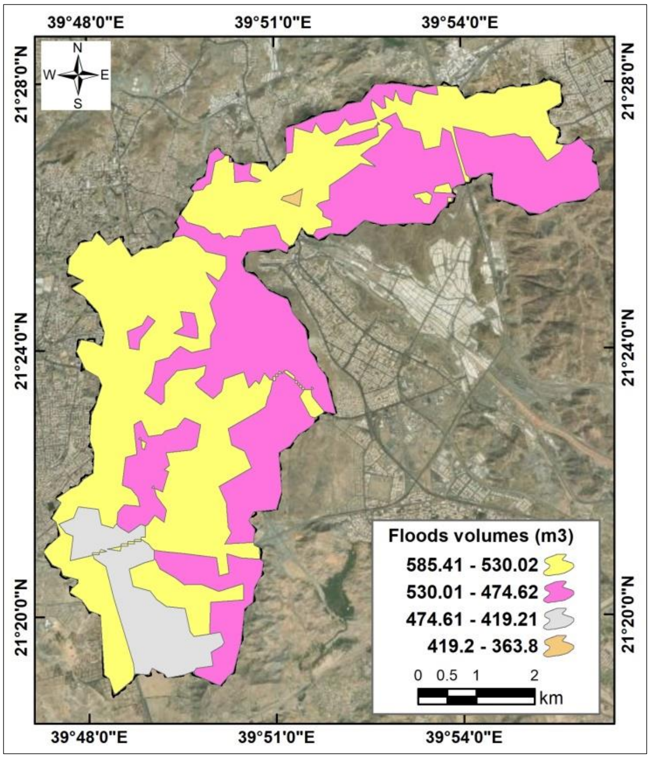


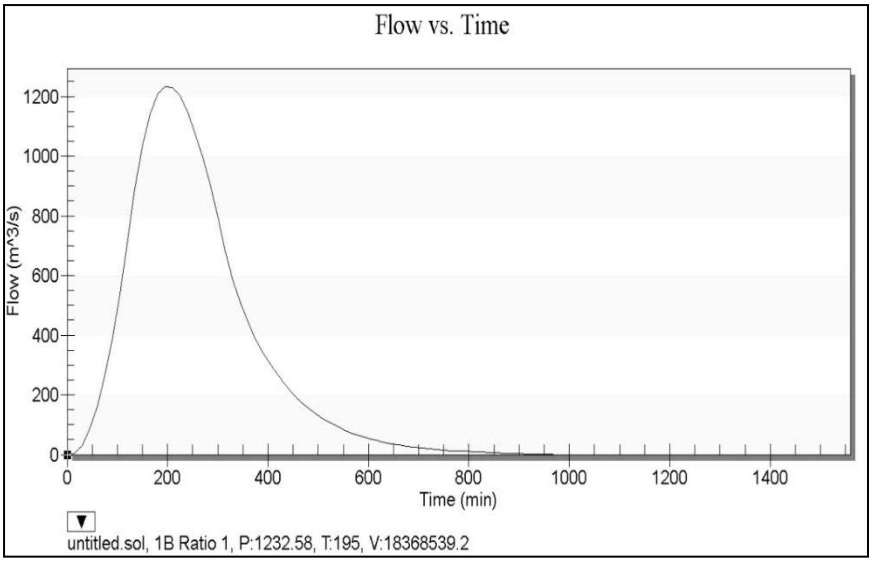
Figure (8): Runoff volume (m^3) in the studied area.

By applying Equation (1), the volume of surface water runoff of the Wadi Ibrahim Basin was calculated at the level of each pixel from the studied basin. Results show that they ranged between 363.8 m^3 and 585.41 m^3, with an average of 556.40 m^3, with a standard deviation of 30.57. The total runoff in Wadi Ibrahim Basin reached 14523940.57 m^3, which indicates the high volume of flow in the basin relative to its surface area (Figure 8). The time of concentration, that expresses the time it takes for water from the upper headwaters of the basin to reach the downstream point through the road network, is about 3.21 hours. This was estimated following Equation (5). Thus, the urban road network is affected by the flash flood hazard throughout this period, which affects the movement of vehicles and people.

3.3. Hydraulic Simulation of Flash Flood Movement

To simulate the movement of torrent on road networks in the city of Mecca, the hydrograph of the torrent was prepared for the studied basin: which expresses the relationship between the volume of water flow and time. It is useful for designing means of protection from the possible dangers of floods in road infrastructure networks, especially when determining the diameter of the flow drainage channels while relying on a return period of 100 years.

By reading the hydrograph of the flow of the peak of the torrent in the road networks in the mainstream in the Wadi Ibrahim Basin (Figure 9), it is clear that the intensity of the torrent increased starting from the 195th minute, to record the maximum water discharge (1232.58 m^3/s). This affects the efficiency of roads and the movement of vehicles and individuals on them, which requires the absorption of torrential drainage channels for this amount of torrential flow. In the case that they are not absorbed, the torrent sweeps away everything that corresponds to it and its risk increases. Accordingly, while designing drainage channels, it is considered to choose the appropriate diameters for the amount of torrent according to such hydrograph (Figure 9).



Source: Data analysis using the HEC-HMS software program.

Figure (9): Hydrograph for the flow of the peak torrent in the road network in the Wadi Ibrahim Basin considering a return period of 100 years.

Depending on the rainstorm hydrograph or the maximum peak of water discharge, it is possible to simulate the movement, direction and height of the torrent, as well as to interpret the variation of its characteristics spatially and temporally, using hydraulic simulations. This is useful in identifying the damage associated with the different stages of the flash flood, as well as possible social or economic losses (Meghan et al., 2011). To do that, the HEC-RAS software program was used in the production of one-dimensional (1D) models that enable the calculation of the parallel and non-parallel flow of the main flow, as well as two-dimensional (2D) models that require high-quality data and sufficient time in their preparation. The model was developed based on the maximum water discharge calculated through the hydrograph of the torrent to determine the flooding areas and determine the water depth and water speed level on road networks and streets surrounding buildings in the catchment area for a rainfall event for a return period of 100 years.

The hydraulic modeling process in this study began with a polygon drawing for the two-dimensional flow area in the Wadi Ibrahim Basin to reveal the central lines of the discharge of waterways and clarify the depressions in the surface of the basin, which helps to represent the flow of sudden flood water. This was achieved using the tools of the Engineering Data Editor - SA/2D Area BC Lines (HEC-RAS toolbar). Due to the mountainous nature of the city of Mecca and the fact that the road networks take the paths of the valleys, hydrological data were added to the detailed digital terrain data to build a two-dimensional network to help the model to perform calculations and determine the directions and depth of the torrent water on the road networks.

Applied studies, including Ramsbottom et al. (2006) have proven that the HEC-RAS program is an appropriate tool for studying the risk of flash floods on the road network expected to be flooded, simulating the possibility of flash floods, and detecting urban infrastructure problems, during a rainstorm with a return period of 100 years. Naeem et al. (2021) showed that if the depth of flow exceeds 0.25 m, it is considered as life-threatening and affects the urban infrastructure and surface networks.

4. Results and Discussion

By applying the two-dimensional hydraulic simulation to the studied area (Figure 10), and considering the field observation data of the urban road network, the following results have been achieved:

4.1. Identifying buildings and road networks affected by flash floods

Flash flood-affected urban road networks were identified during a rainstorm designed for a 100-year return period. The analysis showed that the threshold of the depth of the torrent is likely to reach 150 cm, which in some places exceeds the maximum risk factor on road and street networks (Naeem et al., 2021), which affects negatively the infrastructure and surface networks. Such places are distributed geographically in the central neighborhoods of the city of Mecca Al-Mukarramah within the Wadi Ibrahim Basin, which are as follows:

4.1.1. The Holy Mosque in Mecca

The area of the Grand Mosque in Mecca includes the following sites: Ajyad Al-Sadd, Ajyad Al-Masafi, Bir Balila, and the area surrounding the Holy Mosque in Mecca, all of which belong to the municipality of Ajyad, and these areas have witnessed severe floods, including the torrent (Al-Jahaf), whose damage extended to the Grand Mosque, where the water level reached the door of the Holy Kaaba.

These flash floods resulted in Wadi Ibrahim, which passes through the Haram Al-Sharif area, but considering that means of protection were established, represented in a channel to modify the course of the torrent at the intersection of Hajj Street with Justice Park. Thus, the water of the torrent of the most important tributaries of Wadi Ibrahim was transferred and diverted to Wadi Arna outside the area of the Holy Haram south of Mecca. Despite the modification of the course of the torrent, these areas are still affected by sudden high torrents, except for the location of the Holy Mosque, due to the presence of a highly efficient infrastructure network surrounding it.

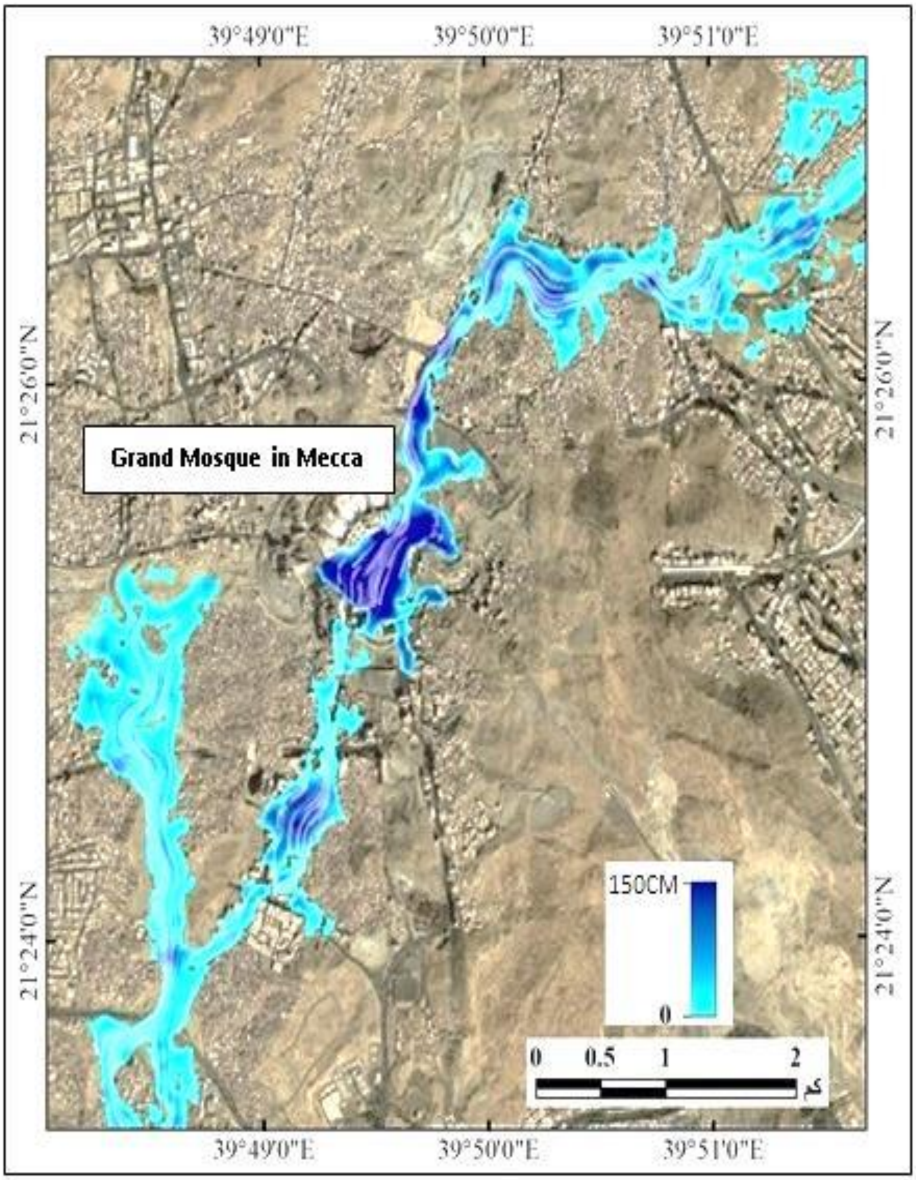


Figure (10): Hydraulic simulation of water flow in the Wadi Ibrahim Basin during the studied rainstorm.

The hydraulic simulation of the flow showed the risk of the flow on the road network and buildings (Figures 11,12,13). We noted the increase in the depth and speed of the water, due to the steep slope of the roads and their location within the course of the tributaries of Wadi Ibrahim Basin, especially Al-Hijra Street, Ajyad Street and Ibrahim Al-Khalil Road.

Figure (11): Plots show the location of the spillway and the severity of the risk of torrent flow in the Holy Mosque of Mecca area.

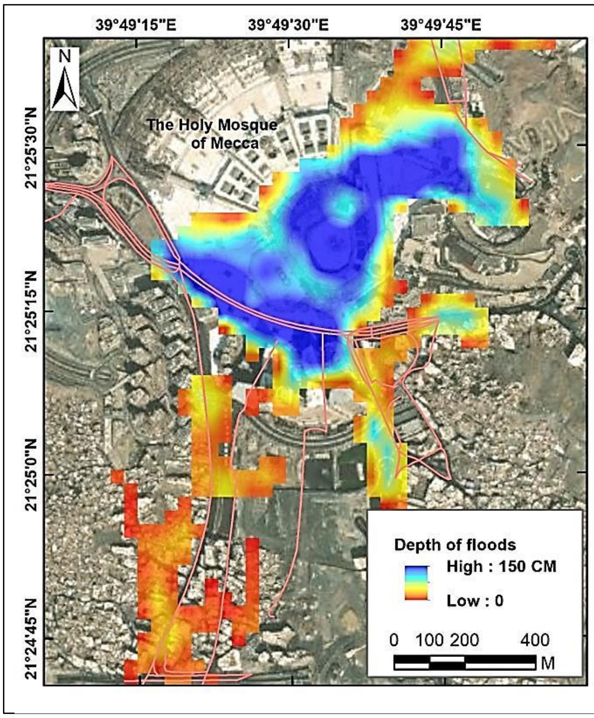


Figure (12): Hydraulic simulation for automatic identification of buildings and roads at risk during a flash flood in the Holy Mosque of Mecca.

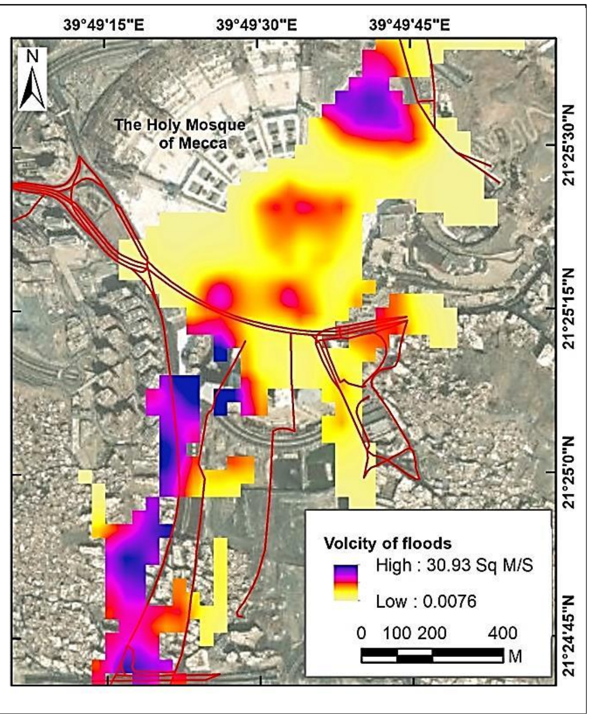


Figure (13): Hydraulic simulation of water speed on buildings and roads exposed to the risk of flash flood in the Holy Mosque of Mecca surrounding area.

4.1.2. Al-Masfala[1] area in Mecca

It is located within the municipality of Al-Misfalah, which is one of the historical lanes of Mecca. The hydraulic simulation of the flow explained that the buildings and the road network (Al-Hijra Street - Ajyad Street - the intersection of the Second Ring Road with Al-Hijra Street) are quickly affected by possible torrents. This is due to the steepness of the surface and the

1 -Its name due to its low level from the level of the Grand Mosque, so the people of Mecca called it “Al-Masfala”.

decrease in the level and the increase in the depth and speed of the water, as well as because the street network takes from the main course of the torrent as its path, which resulted in the accumulation of water and an increase in its depth and speed, as it appears clearly in Figures (14,15,16,17).

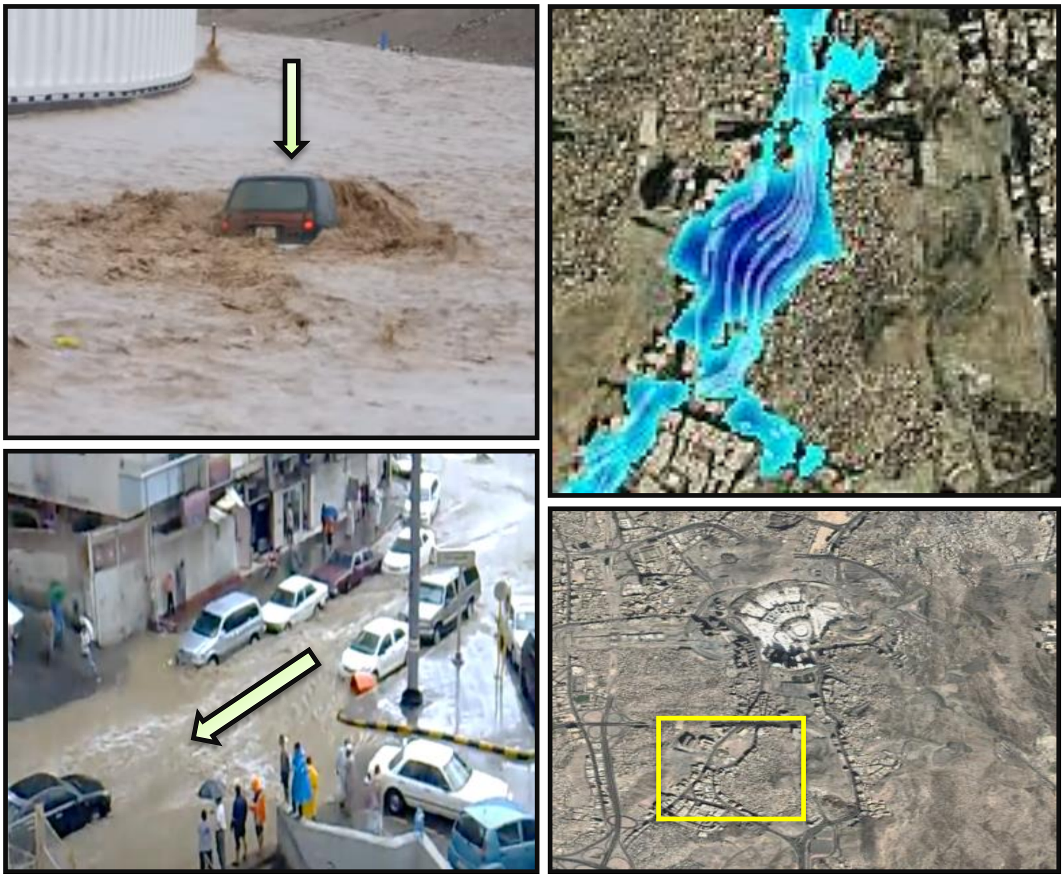


Figure (14): Plots show the location of the spillway and the severity of the risk of torrent flow.

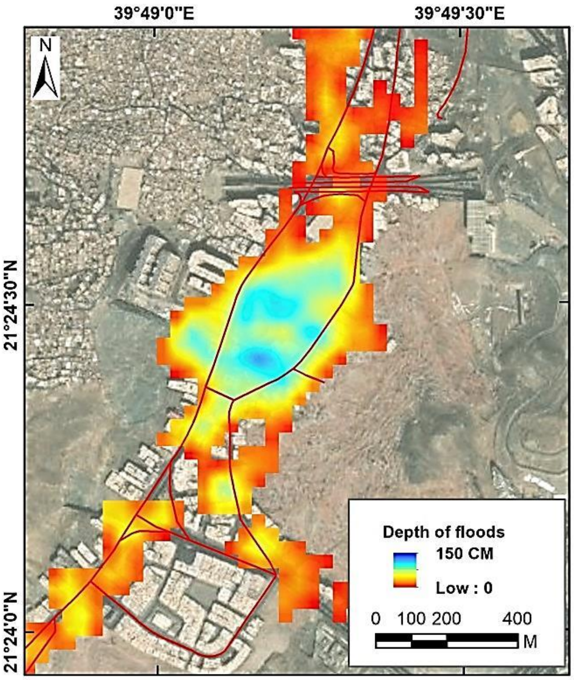


Figure (15): Hydraulic simulation for automatic identification of buildings and roads exposed to the risk of flash floods in the Al-Masfala area, south of the Holy Mosque of Mecca.

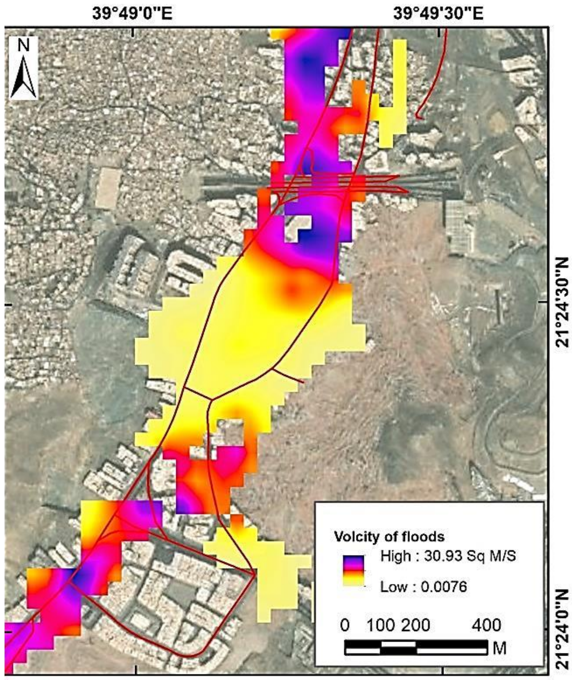


Figure (16): Hydraulic simulation of water speed on buildings and roads exposed to the risk of flash floods in the Al-Masfala area, south of the Holy Mosque of Mecca.

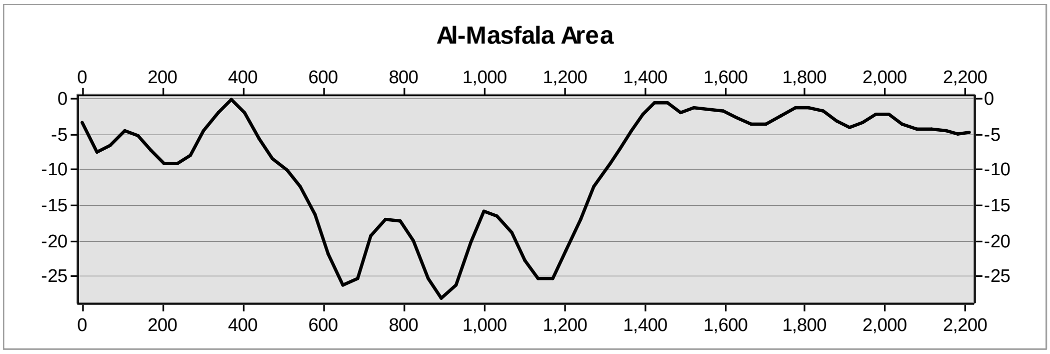


Figure (17): A cross section on the road axis showing the depth of the water.

4.1.3. Elmaabda area

It is located in the Al-Maabdah neighborhood, northeast of Mecca Al-Mukarramah in Wadi Ibrahim Basin, about 2.0 km from the Grand Mosque, and extends from Al-Hujoon Bridge to the beginnings of "Feelings". Through hydraulic simulation of the flow shown in Figures (18,19,20), it was found that the temple is classified among the places where high flow is likely to occur. This is the result of the confluence of the tributaries of Wadi Ibrahim in this place and the accumulation of water and the steepness of the surrounding mountains, such as Al-Nour, Khandama and Al-Sayyida, and Taif / Al-Sail Road that is considered as one of the most important roads that fall under the influence of the torrent during its occurrence. Also, Al-Abtah Street, and Justice Square, where the depth of the water ranges from 9.0 cm to 16.25 cm, and the water speed increases to reach 29 m/s at the Justice Bridge, where the intersection of the third Drairi with Hajj Street.

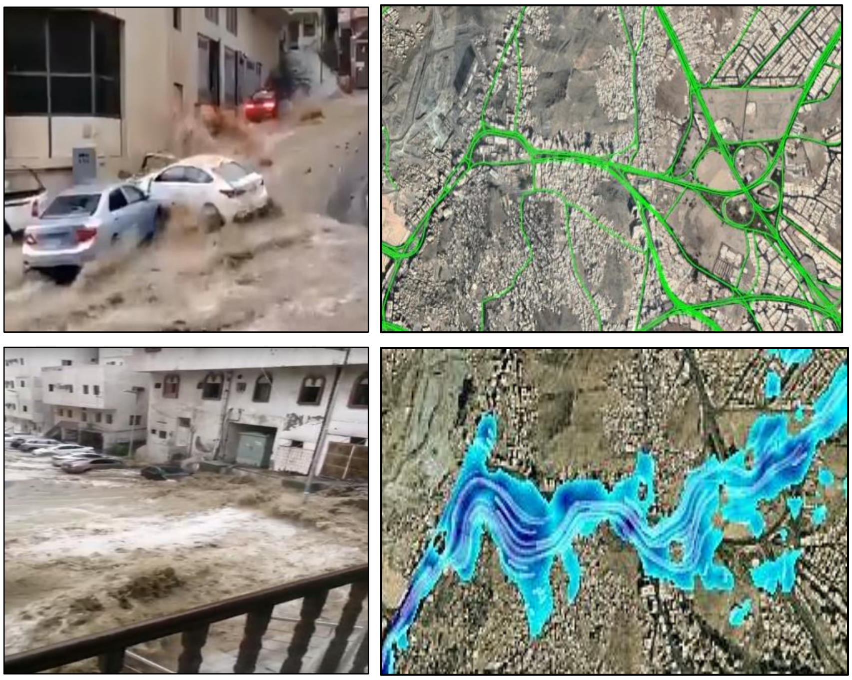


Figure (18): Plots show the simulation of torrent flow and its risk in Al-Adl Square, where the intersection of Al-Hajj Street and Raya Zakher.

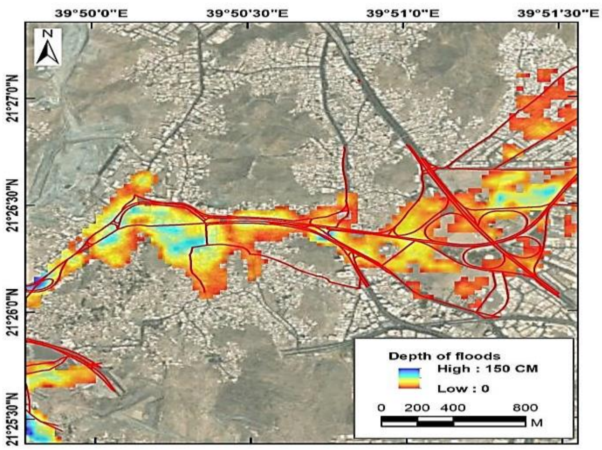


Figure (19): Hydraulic simulation for automatic identification of buildings and roads at risk in the Al-Maabada area (Rai Zakher and Justice Square).

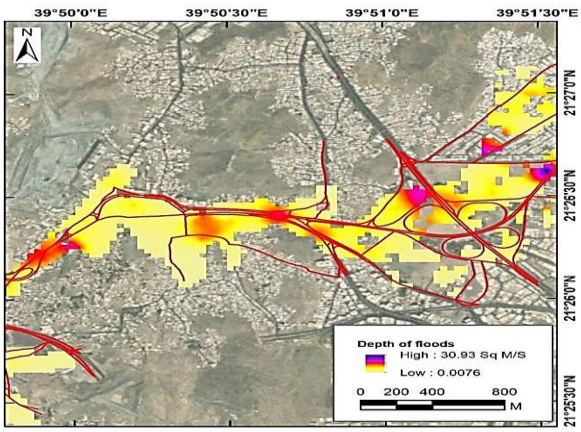
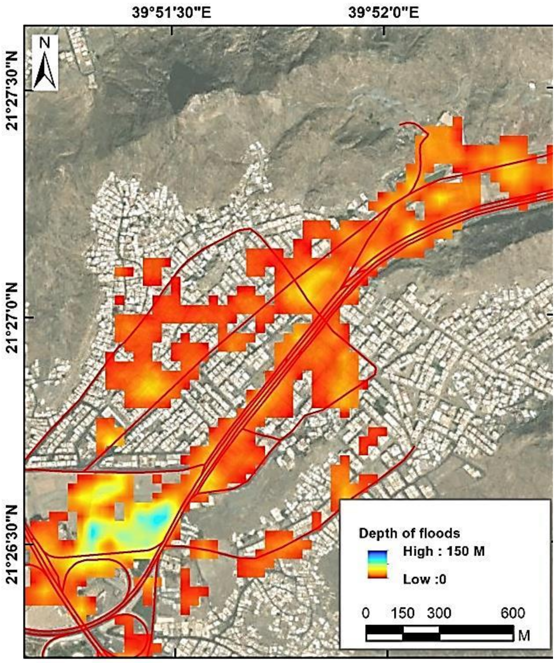


Figure (20): Hydraulic simulation of water speed on buildings and roads exposed to risk of flooding in the Al-Maabada area (Rai Zakher and Al-Adl Square).

4.1.4 Jabal Al Nour Plain

Jabal al-Nour is located to the northeast of Mecca Al-Mukarramah, and passes through the center of the Jabal al-Nour scheme, the main stream of Wadi Ibrahim, which is also the Taif / Al-Sail road, and the result of the proximity of the Al-Nour scheme to the areas of the sources of Wadi Ibrahim and the height of the mountainous areas surrounding it. A large number of buildings were exposed to the influence of Al-Sail (Figures 21,22), and special roads are located by Taif/Al-Sail Road, which is a main road linking the city of Mecca Al-Mukarramah with the city of Taif, and Jabal Al-Nour Street, where the speed and depth of water increases, up to 30 m/s and 70 cm, respectively.



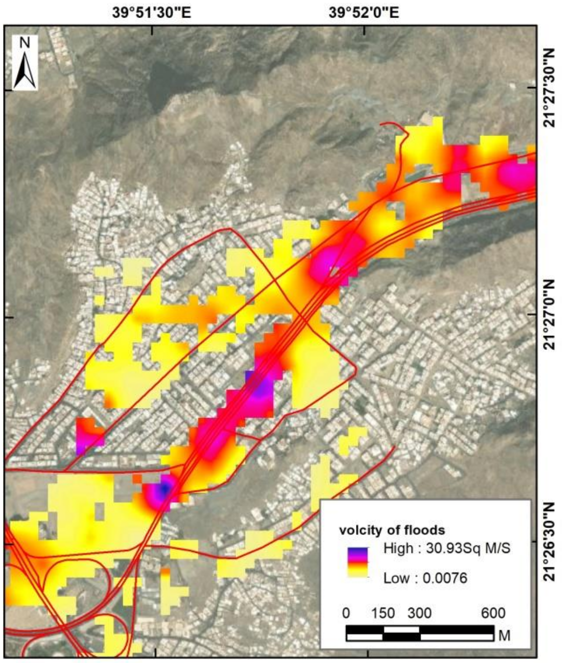


Figure (21): Hydraulic simulation for automatic identification of buildings and roads at risk in the Al-Maabada area (Al-Ghasa and Jabal Al-Nour plains).

Figure (22): Hydraulic simulation of water speed on buildings and roads exposed to the risk of flooding in the Al-Maabada area (Al-Ghashalla and Jabal Al-Nour plans).

4.1.5. Batha Quraish plain

It is located in the municipality of Al-Shawqiya, and it is one of the sites threatened by flash floods in the city of Mecca Al-Mukaromah (Figures 23,24), as it passes through one of the main tributaries of the Wadi Ibrahim Basin, which originates from the top of the Mina Mountains. This scheme has been exposed for a long time to the flash flood hazard, which resulted in spatial problems, specifically the location of the Batha Quraish walkway and the Grand Mosque road, where the speed and depth of the water increase, reaching 30 m/s and 52 cm, respectively.

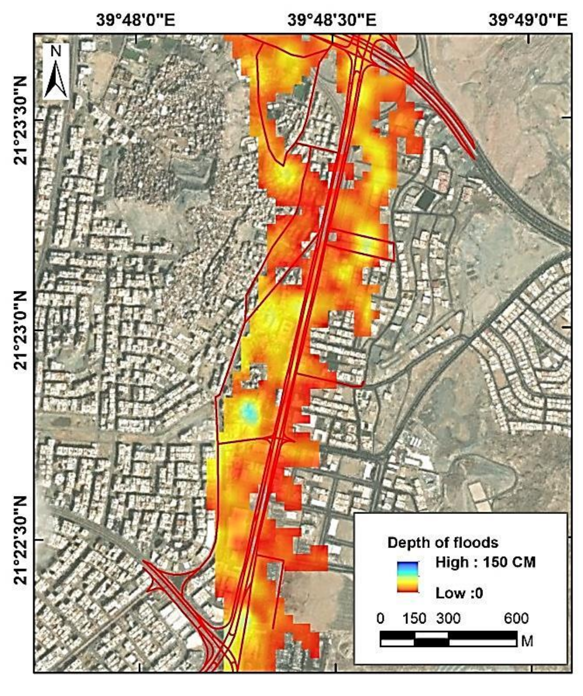


Figure (23): Hydraulic simulation for automatic identification of buildings and roads at risk using the Batha Quraish diagram.

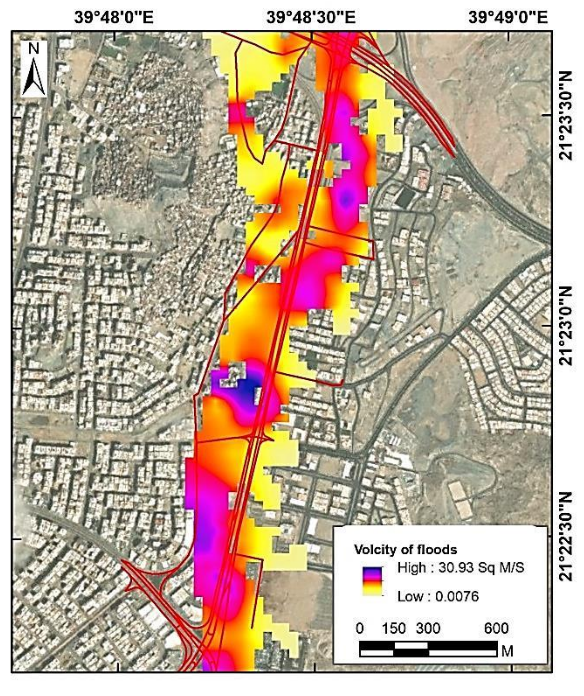
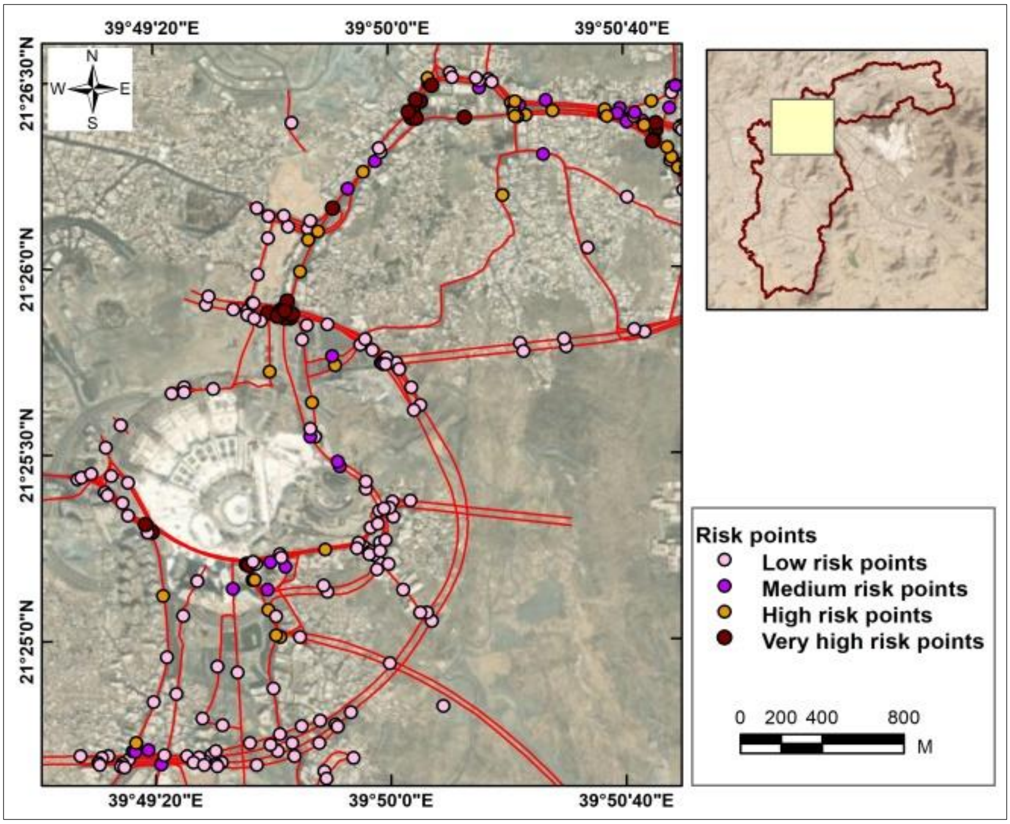


Figure (24): Hydraulic simulation of water speed on buildings and roads exposed to the risk of floods according to Batha Quraish diagram.

Through the analysis of hydraulic simulations, the points at risk on the road network in the studied area (Figures 25,26,27,28) were determined, where they were classified into four categories, namely: low, medium, high and very high risk. High-risk points are located in the following places: the Grand Mosque Road at the intersection of Al-Saqqaf Street in Al-Maabda area, the intersection of the Second Ring Bridge with the Grand Mosque Road in the Gaza area, the intersection of

Al-Hijra Street with the Second Ring Road in Al-Misfala Municipality, Al-Mansour Street near the Second Ring Road, the intersection of Ibrahim Al-Khalil Street with Dr. Abdullah Koshak Street, and finally the intersection of Al-Mansour Street with Jarham Street in Al-Misfala Municipality.



Source/Hydraulic simulation analysis of floods

Figure (25): Classification of points at risk for flash floods in El-Haram area.

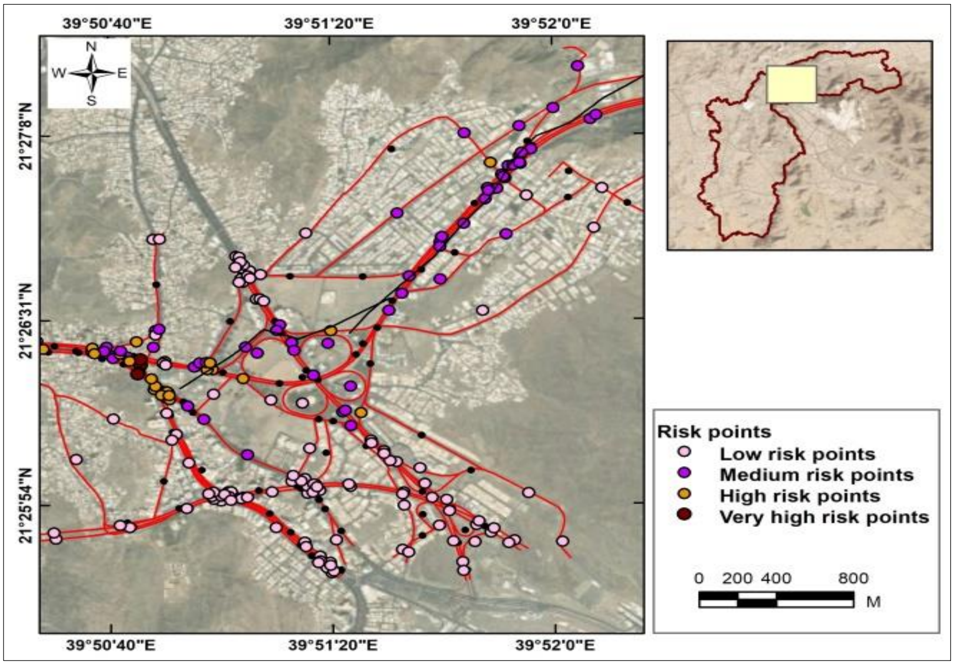


Figure (26): Classification of points at risk for flash floods in Jabal Elnour area.

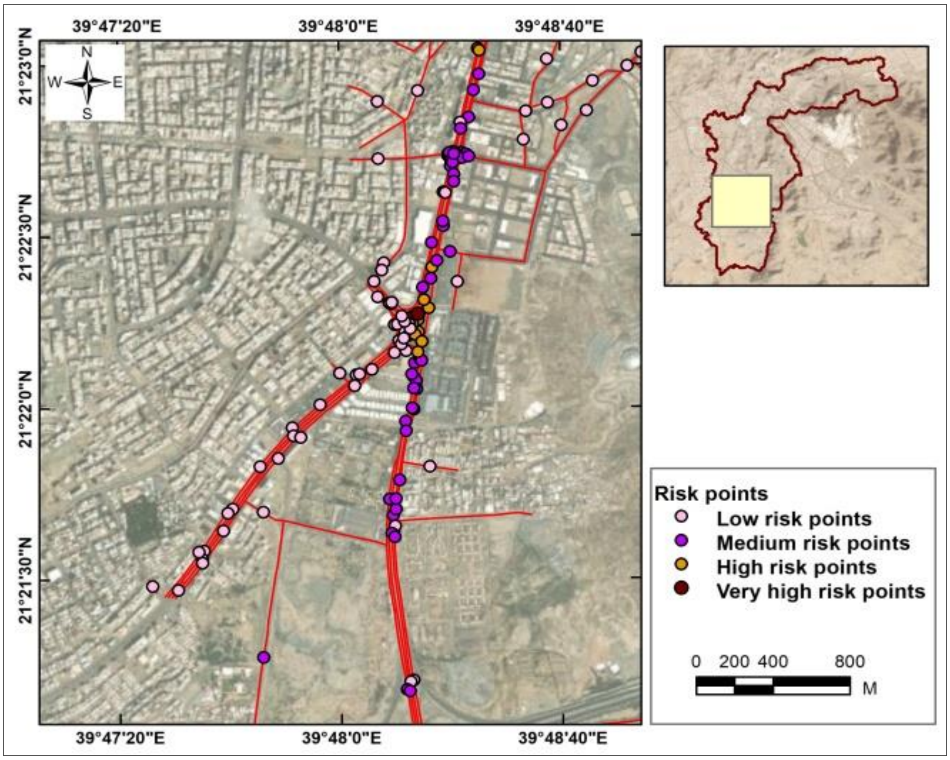


Figure (27): Classification of points at risk for flash floods in Al Shwqiyya area.

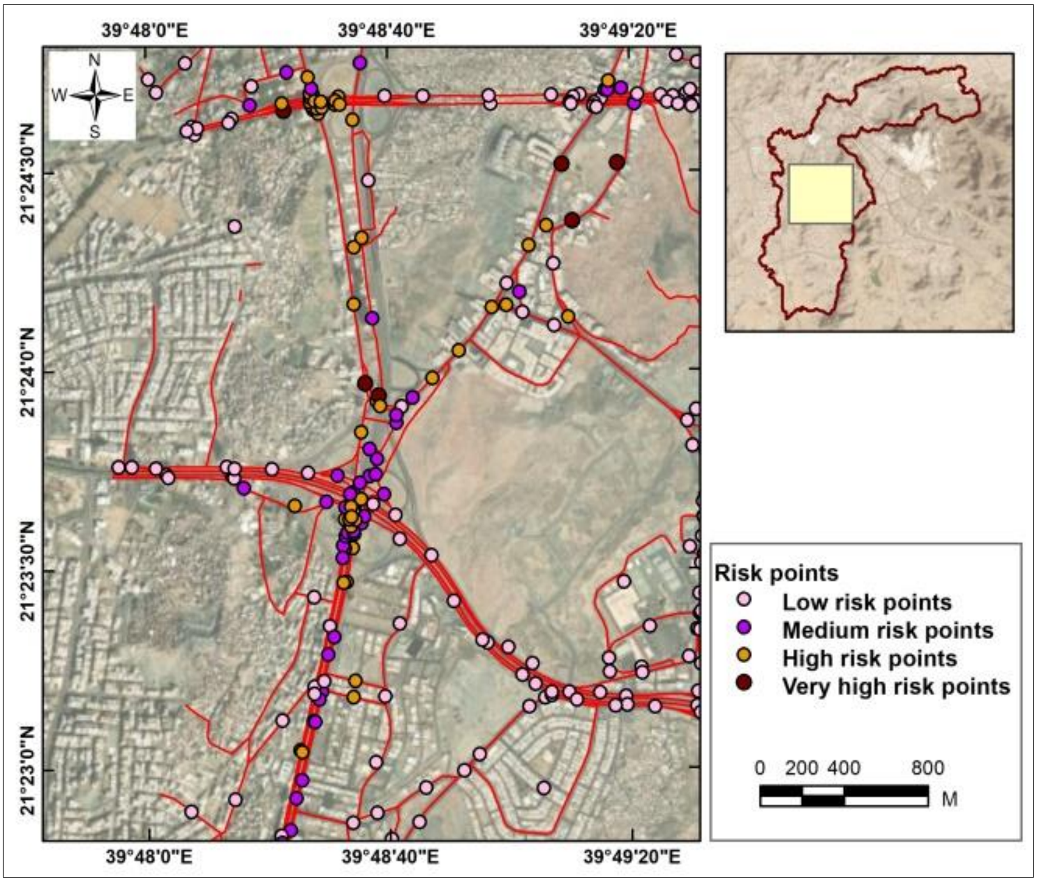


Figure (28): Classification of points at risk for flash floods in Batha Qurish area.

4.2. Evaluation of the flood drainage network

The city of Mecca Al-Mukarramah has a drainage network for torrents with a total length of 226 km, and varies between closed, tubular and deep tunnel box channels, in addition to surface and open drainage channels. Additionally, work is underway throughout the year to implement maintenance and cleanliness plans to be largely ready to receive the rainy season at any time (Flood Management: Mecca Municipality, 2019). The Municipality of the Holy Capital conducts maintenance and cleaning work for all these networks on an ongoing basis and has implemented flood drainage networks in residential neighborhoods and linked them to the existing network. The drainage network in Mecca has been designed to be in four main directions that correspond to the general slope of the surface and the directions of the surrounding valleys. The first one is the northern exit where the path of Wadi Yaj, the second is the eastern exit where the Husseiniya path, and the third is the southern exit where the path of Bir Yakhour (Figure 29). Furthermore, the Municipality of Mecca Al-Mukarramah has developed many sites that were witnessing spatial problems as a result of heavy rains, and worked to prepare them through some projects to absorb large quantities of water and discharge it outside the basin to reach natural sewers. In the following, a review of the most important projects:

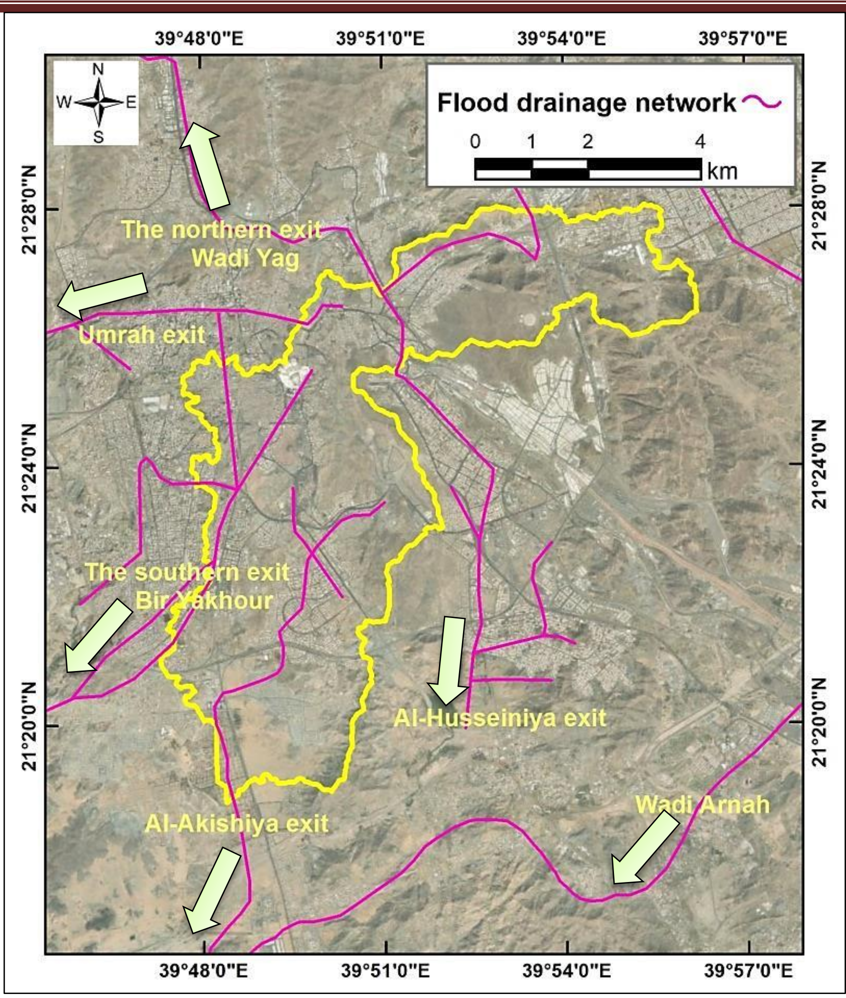
4.2.1. Yakhour well water drainage project

It includes the southern exit that transports the flow from the Haram al-Sharif area through Wadi Ibrahim to the exit of Bir Yakhour located in the Kaakia area outside the urban area. This could reduce the risk of such water, as they were causing harm to citizens south of the Grand Mosque in Mecca.

4.2.2. Al-Awali and Al-Husseiniya direction drainage project

It includes the southern exit that aims to drain rainwater and torrential rains coming from Aziziyah and the holy sites south beyond the boundaries of construction (Figure 29).

Figure (29): Photographs show means of protection from the flood risk in the Shawqia area in Mecca Al-Mukarramah.



Source: Flood Management, Mecca Municipality (2019)

Figure (30): The axes of the flood drainage network in the city of Mecca.

The low efficiency of the drainage network in unplanned places is due to the incompatibility between the diameter of the drainage channels and the extent of their response and absorption to the top of the water drainage designed for a sudden rainstorm with an annual return period of 100 years (Figure 31), and this is illustrated by the hydrograph of Wadi Ibrahim where the water discharge reaches 1232.58 m^3/sec. In this regard, the hydraulic structures – according to the current design specifications – do not absorb this quantity in a short time that does not exceed three hours, which affects the structure of the roads and the efficiency of vehicle movement on them.

Figure (31): Photograph shows the poor absorption of the flow drainage network and the exit of water from the main hole.

There are also no channels that transfer torrential water to the main channels of the flow drainage systems in some popular unplanned places in the city of Mecca, where the network does not include all streets. Additionally, there are problems in the design and implementation of these channels, including: the factor of the degree of slope of the surface, which is characterized by its intensity, the factor of solid rock formation, and the factor of residential pattern close to each other. In the face of these spatial problems affecting the risk of the torrent in the city of Mecca, the focus is on the sites of intersections in the main and secondary streets, where torrential water collects, and the preparation of links from the drainage channels linking them to the main network, especially in the sites of the popular lanes that are characterized by the slope of their streets (Figure 32).

Figure (32): Pictures show means of protection from flowing on construction in the scheme of Batha Quraish in the municipality of Shawqia.

5. Conclusions

The accurate application of GIS is a great necessity in addressing environmental challenges such as managing the risk of flash floods on road networks and buildings in urban areas that frequently occur to rainstorms. GIS has a great ability to integrate and analyze diverse data sets, and turn them into practical and actionable visions to protect infrastructure, buildings and road networks against the risk of flooding. However, the essence of an effective flood management strategy goes beyond just technological applications, it may include a holistic approach that blends technology accuracy with effective community engagement through integrated risk assessment. The current study showed that hydraulic simulation of flood scenarios is a powerful tool in predicting potential flash flood risks and planning accordingly. Involving local communities in flash flood risk management is also critical by raising awareness and participating in risk mitigation strategies. Intersectoral collaboration is also vital to improve the use of GIS in flood management. Furthermore, the establishment of robust early warning systems is crucial. These systems should be able to provide timely alerts to residents, allowing for effective emergency responses on road networks, as such systems can play a vital role in reducing the impact of floods when they occur.

Although natural disasters cannot be completely prevented, there are proactive measures that can significantly reduce physical damage, and one of the keys to these measures is flash flood control, a concerted effort to reduce the impacts and losses caused by flooding. This includes a systematic process that begins with the identification of buildings and road networks at risk of flooding. This makes GIS applications broad and diverse, extending beyond traditional mapping, helping in the design and management of cities in the field of urban planning, and helping to balance development and environmental sustainability.

The current study of Mecca recommends the continuous maintenance of flood water drainage facilities represented by the drainage channel towards the Yakhour well and Awali in the south and the direction of Umrah in the north. Additionally, the need to expand the establishment of hydraulic facilities for the control and obstruction of flood water is crucial. Furthermore, increase the width of the diversion channel in Wadi Ibrahim (a breadth of at least 170 m) is highly recommended, so that it can transfer water drainage from the area of the Grand Mosque in Mecca to the course of Wadi Arna. Criminalizing construction in the sewers of Wadi Ibrahim and flood catchment areas and the need to carry out mandatory studies of the risks of flash floods and restrict building permits in the tributaries of Wadi Ibrahim are essential. The importance of expanding the southern channel at the Yakhour well to reduce the height of the water, as well as the resulting dangers that threaten the road network and buildings, so that its width will becomes of not less than 200 m. The need to adopt a plan to harvest floodwater in the upper reaches of Wadi Ibrahim and exploit them for population purposes and various economic activities. From a geotechnical point of view, the establishment of an early warning system that includes an interactive interface that citizens and residents can benefit from through the instructions directed by the flood management to them during the occurrence of rainstorms. These proposed alternatives came to mitigate and reduce the possible risk of flash floods in line with the plan and vision of the Kingdom of Saudi Arabia 2030.

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