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ORIGINAL PAPER

Projected impacts of land use and road network changes on increasing flood hazards using a 4D GIS: A case study in Makkah metropolitan area, Saudi Arabia

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Abstract Makkah City, west of the Kingdom of Saudi Arabia, is considered the third main highly populated metropolitan area in the Kingdom of Saudi Arabia. It exhibits two unique features that increase the hazardous flood consequences: (1) its topography is very complex and (2) about three million Muslims are gathered annually in Makkah to perform Hajj over a 2-week period. Floods are natural returning hydrological phenomena that have been affecting human lives. The objectives of the current study are: (1) identification of land use types and road networks in Makkah, (2) hydrological modeling of flood characteristics in Makkah based on precise up-to-date databases, (3) examination of the relationship between land use, land cover changes, transportation network expansion, and the floods' prosperities and hazards, and (4) development of digital hydrological maps for present and near future flood hazards in Makkah. The attained results show that the mean runoff depth and the total flood volume are significantly increased from 2010 to 2030. Additionally, it has been found that a great part of the road network in Makkah City is subjected to high dangerous flood impacts. The overall length of flood danger-factor roads is increased from 481 km (with almost 37 %) to 1,398 km (with 74 % approximately) between 2010 and 2030. Thus, it is concluded that urbanization has a direct strong relationship with flood hazards. Consequently, it is recommended that the attained results should be taken into account by decision makers in implementing new development planning of the Makkah metropolitan area.

Keywords Flood management · Road networks · Urbanization · GIS · Makkah

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Introduction

Flash floods occur periodically in Makkah City, Saudi Arabia, due to several factors including its rugged topography and geological structures. Hazards of flash floods are vital in terms of human lives lost and economical damages. Hence, precise assessment of floods becomes a more vital demand in development planning (e.g., Subyani et al. 2010; Fred and Mostafa 2008). A Geographic Information System (GIS)-based methodology has been already developed to quantify and spatially map the flood characteristics (Dawod et al. 2011a). Utilization of a precise Digital Elevation Model (DEM) enables precise flood modeling in Makkah (Mirza et al. 2011a, b, c). Simple rainfall-runoff models (e.g., Snyder and regression models) did not take into account important parameters particularly the land use and land cover of the catchment area. Land use plays a central role in flood runoff and, consequently, in flood hazardous impacts. Generally, flood runoff reacts differently with respect to land covers and road network locations. Global and national flood modeling methodologies implicitly take into account the types of land use in the catchment area. One of the most popular flood model is the US National Resources Conservation Services (NRCS) curve number (CN), which has been applied globally for flood modeling (e.g., Chen et al. 2010; Mojaddadi et al. 2009).

The relationship between land use changes, road network expansion, and the increase of flood hazards has been investigated by a number of researchers. This issue may not have acquired the necessary awareness in Saudi Arabia although it is considered a major subject in hydrological and environmental planning, and many governmental organizations, in several countries, have focused on that dilemma. For example, research studies and practical projects have been carried out in: the USA (e.g., Wang et al. 2010; Sheng and Wilson 2009), France (e.g., Paquier 2010), and New Zeeland (e.g., Hansford 2010). Consequently, land use and road networks are key factors affecting flood runoff volume and path (e.g., Sherief 2008).

Regarding the influences of land cover changes on flood peak discharge, Olang and Furst (2011) have studied the impacts of historical land cover changes witnessed between 1973 and 2000 on the hydrologic response of the Nyando river basin in Kenya. Physically based parameters of the models were estimated from the land cover change maps together with a digital elevation model and soil datasets of the basin. Results revealed significant and varying increases in the runoff peak discharges and volumes within the basin. A similar study has investigated the land use/flood dilemma in India, but from a different perspective (Kar et al. 2009). That research aimed to study the morphometric and hydrological properties of a watershed and tried to get benefits of those properties in enhancing land use sustainable planning. Other investigations have focused on the assessment of land uses and also population distribution on hydrological section properties. An approach was developed to quantify the landscape alterations resulting from human disturbances (e.g., urbanization, agriculture, roads, and population) on lake conditions in Michigan state, USA (Wang et al. 2010). More recently, the relationship between urbanization and flood hazards has been investigated extensively utilizing geomatics technologies particularly the GIS. Amini et al. (2011) concluded that land cover deterioration has increased the flood peak by up to 26.7 % in the Damansara watersheds, Malaysia. Similar results reveal that increasing development (in Los Angeles, CA, USA) increases total annual runoff and decreases groundwater recharge during both dry and wet seasons (He and Hogue 2011). Also, a special flood warning system is proposed for road networks in particular (e.g., Versini et al. 2010).

Based on results of related investigations worldwide, it can be concluded that inspecting the impacts of land use changes and road network expansion on flood hazards in Makkah metropolitan area becomes an obligation. It is worth mentioning that the metropolitan extent of Makkah City has been increased from 4,800 ha in 1983 to 9,457 ha in 2004 (Mirza 2009). Also, new circular highways and metro lines are planned in Makkah. Hence, the growing urbanization rate in Makkah nowadays emphasizes the necessity for conducting a scientific project, utilizing recent technical tools and models, to quantify the expected flood hazard increase in the present and near future, particularly in the holy shrines. This study will be the first of its kind to be carried out not just in Makkah City, but in the entire Saudi Arabia.

Study area

Makkah City is located in the southwest part of the Kingdom of Saudi Arabia, about 80 km east of the Red Sea (Fig. 1). The current area of the metropolitan region (the study area) extends about 37 km in the north and 43 km in the east; thus, it equals approximately 1,600 km^2. It extends from longitudes 39°35′E to 40°0′E, and from latitudes 21°15′N to 21°35′N. Makkah City is a unique city for Muslims all over the world, since it contains the holy mosque. From a religious point of view, a Muslim should perform pilgrimage (called Hajj, which means visiting Makkah in specific days in the year) once in his/her life. Thus, hundreds of thousands of Muslims are gathered in Makkah yearly. Moreover, the topography of Makkah is complex in nature, and several mountainous areas exist inside its metropolitan area. That is also a vital element in investigating the spatial pattern of Makkah sprawl.

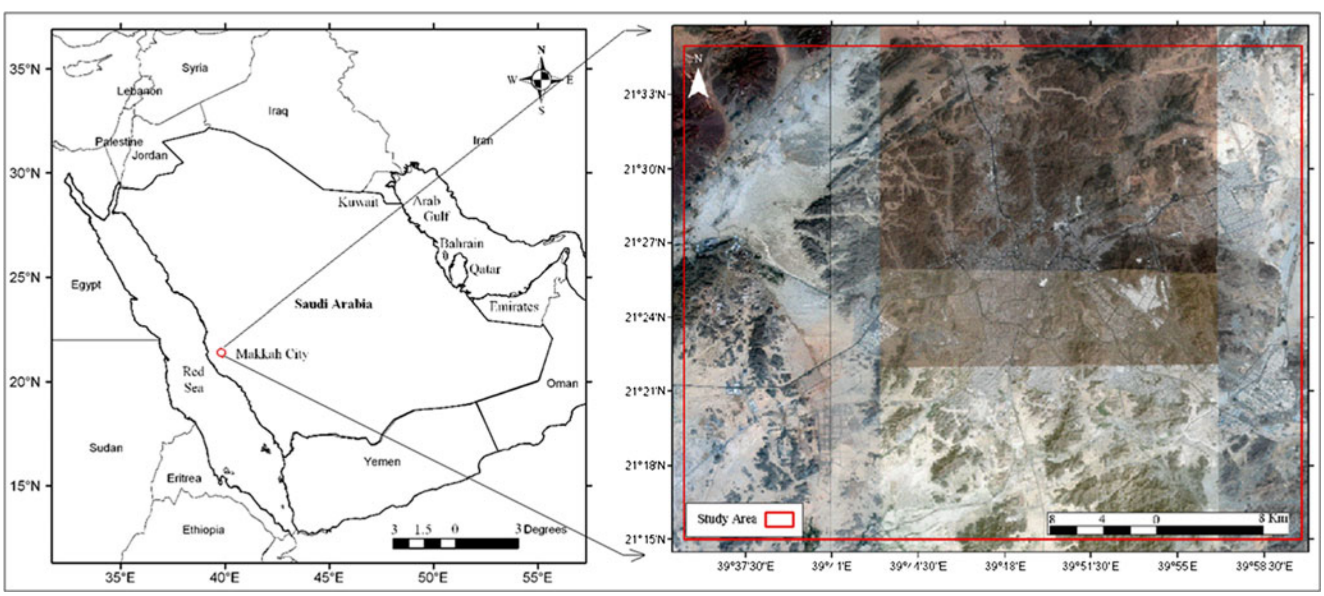

Fig. 1 Makkah City

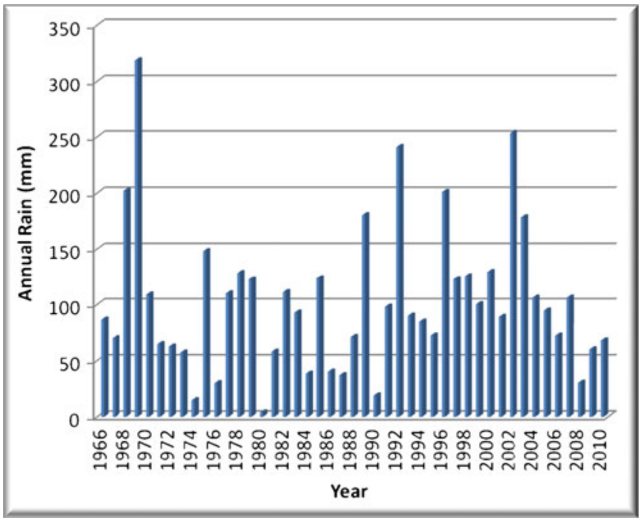

Fig. 2 Annual rains in Makkah City from 1966 to 2010

Makkah's hydrology

It is worth mentioning that the southwest part of the Kingdom of Saudi Arabia contains almost 60 % of the volume of wadi flow, particularly in the terrain situated between the Red Sea coast and the adjacent mountains. The annual rain over Makkah City, for a period extending from 1966 to 2010, varies from 3.8 to 318.5 mm, with the average rainfall equal to 102.6 mm (Fig. 2). Due to the complexity of Makkah's topography, flash floods occur periodically with significant variations in magnitude. Mirza and Ahmed (2001) have reported that the extreme flood type is repeated with a return period of 46 years, while a second-order flood takes place occasionally with a return period of 33 years, and a low-dangerous flood comes about every 13 years.

Makkah's topography

The topography of the Makkah metropolitan area is complex, where several mountainous regions exist within the urban boundaries of the city. Terrain heights in Makkah (Fig. 3) range from 82 to 982 m above sea level (Mirza et al. 2011a, b, c). The highest mountains in Makkah City are: Al-Tarki (987 m), Ahdaab (919 m), Thabeer (814 m), Thour (719 m), and Al-Noor mountain (620 m). Dividing Makkah's heights in groups (Table 1), it can be realized that 81.8 % of the heights are less than 400 m. In the second group, heights range from 400 to 600 m and occupy 17 % of Makkah's area, while 1.1 % has heights ranging from 600 to 800 m. The highest area, with values greater than 800 m, only occupies 0.1 % of Makkah City. Distributions of the topography slopes in Makkah City are also depicted in Fig. 4 and tabulated in Table 2. It can be noticed that about 80 % of Makkah territories have smart slopes of less than 10°, while 0.9 % of the study area represents hilly regions of slopes greater than 30°.

It is known that the growth in Makkah City spreads out along the valleys and stays away from the mountainous areas for economical reasons. It is worth mentioning that almost 50 % of Makkah's geology contains igneous rocks, mainly granite, that massively increase the development costs in mountainous areas.

Fig. 3 Topography of Makkah City

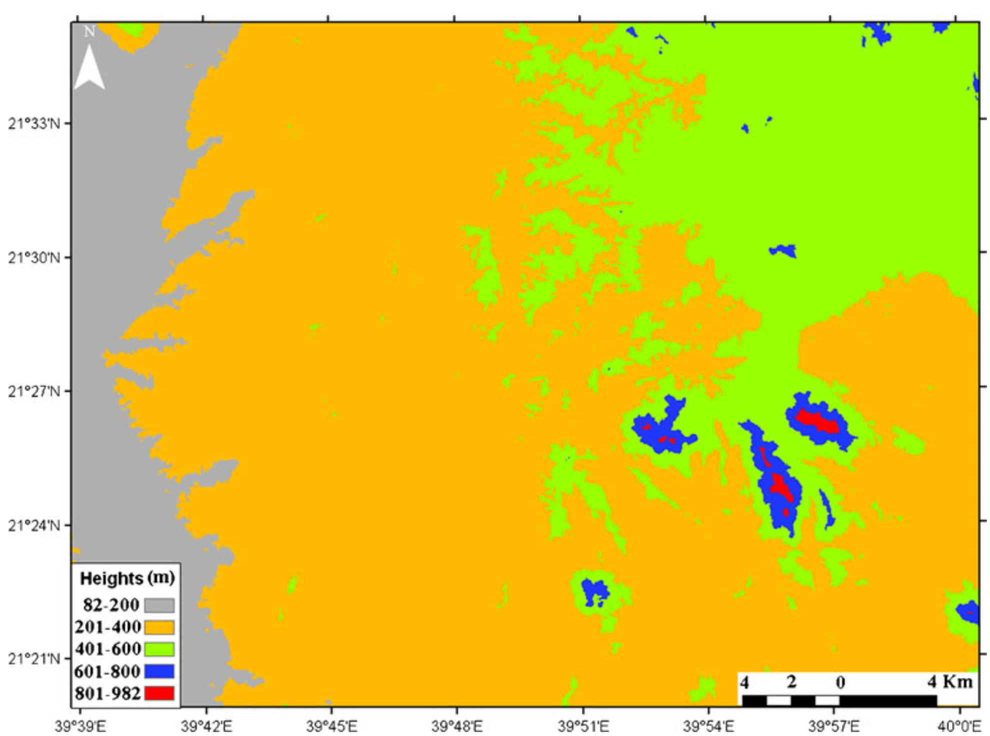

Table 1 Makkah height categories

Heights in meters (above mean sea level)	Area (%)
Less than 400 m	81.8
From 400 to 600 m	17.0
From 600 to 800 m	1.1
Greater than 800 m	0.1

Table 2 Makkah slope categories

Slope (°)	Area (%)
Less than 10°	79.7
From 10 to 20°	15.7
From 20 to 30°	3.7
Greater than 30°	0.9

Makkah's geology

The geology of Makkah metropolitan area consists mainly of three geological structures (Fig. 5 and Table 3). The Precambrian igneous rocks occupy about 809 km^2 (with 51 % approximately of the total area). Those rocks implicitly imply a low-permeability property that increases the ability of rainfall to be converted into dangerous surface runoff. The deposits, or wadi alluvium, exist mainly along the wadi streams and constitute about 48 %, with an area equal to 770 km^2 approximately. The rest of Makkah area, about 12 km^2 only, represents the tripartite rocks.

Available data

The collected databases consist of several data sets of different types, sources, and dates. They include:

- The spatial urban compiled datasets constituting two categories:
  - The first element consists of 105 cadastral maps in AutoCAD files for 1990.
  - The second constituent consists of a land use map developed by the Saudi Geological Survey Authority dated 2010.
  - The third category contains detailed cadastral maps that describe the future Makkah land use and road network in 1,450 H (HAMDD 2004).
- A national 5-m-resolution DEM for the study area has been obtained from the King Abdulaziz City of Sciences and Technology.
- A set of 1:50,000 topographic maps, produced by the Military Survey Department, Ministry of Defense and Aviation.
- A set of 1:50,000 geological maps, produced by the Saudi Geological Survey Authority.
- A set of Ikonos and Quick-Bird high-resolution satellite images.
- A hydrological database obtained from Institute of Hajj and Omrah, Umm Al-Qura University.

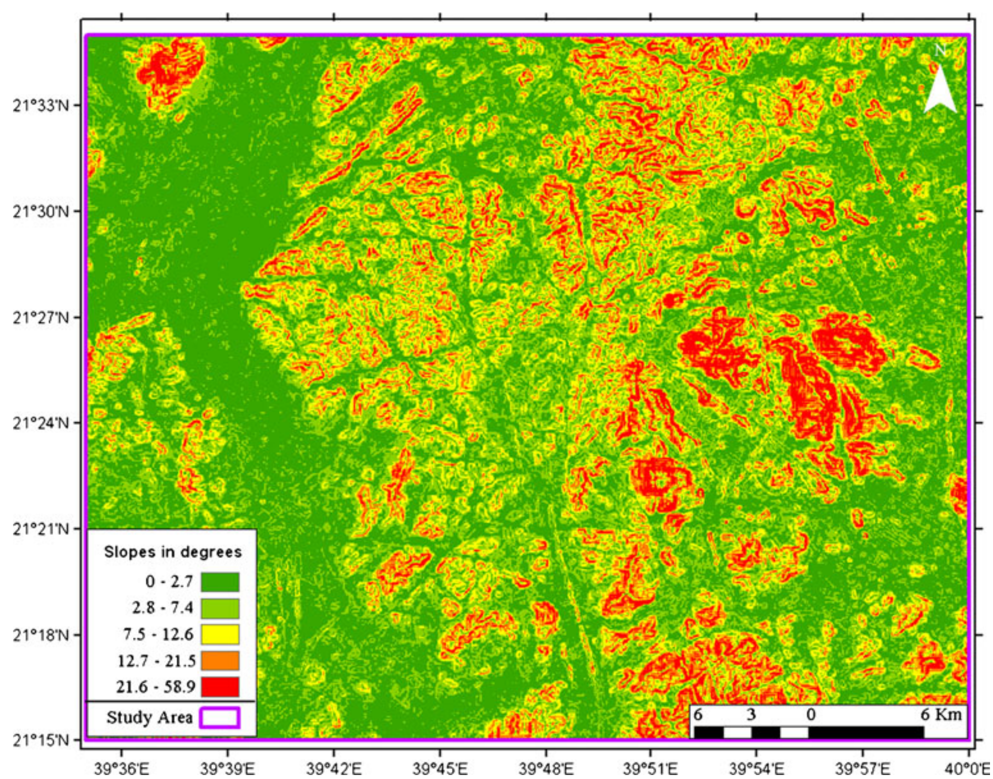

Fig. 4 Terrain slopes of Makkah City

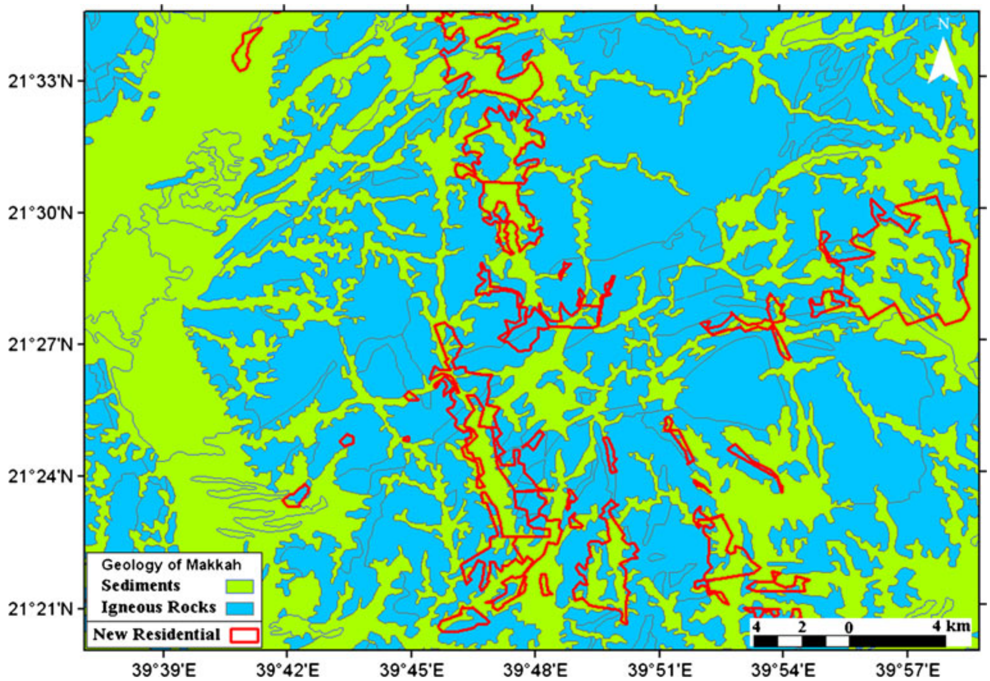

Fig. 5 Geology of Makkah City

Methodology and data processing

Accurate estimation of flood characteristics in Makkah metropolitan area is a vital demand in planning and resources management. The different collected datasets have been manipulated and stored in a digital form after unifying their geographic datums and coordinate systems. In order to extract the hydrological catchments in Makkah City, a morphometric analysis has been performed and utilized as an input step for flood estimation. Then, a unique GIS system has been built for quantifying and spatial mapping of flood hazards in Makkah in past, present, and future scenarios. Impacts of urban growth and flood hazard increase on the road networks in Makkah have been determined. The following sections describe, in detail, the utilized methodology and the procedures applied in data processing.

Building a unique 4D GIS

The developed GIS-based flood assessment methodology consists of several stages. The Arc GIS software (v. 10), along with the Arc Hydro extension, has been used in the present study to combine all obtainable data in a unique environment. The processing phase includes (Fig. 6): rectifying the printed maps, digitizing two shapefiles for residential areas and roads for each dataset, converting AutoCAD files to GIS shapefiles, unifying the spatial reference frames for all datasets, performing statistical and spatial analyses, and flood computations (Al-Ghamdi et al. 2012b). The Arc GIS software has been used to obtain several shapefiles describing the geomorphology of the study area. These shapefiles include: the main basins and the sub-basins of each main catchment, along with drainage network using the Strahler method (a simple widely utilized network order method), and the longest stream path in each catchment. The second stage of the developed methodology is based on the flood assessment method developed by the NRCS, formerly known as the Soil Conservation Service. Processing steps, and hence attained results, have been performed for past (1990), present (2010), and future (2030) scenarios.

Table 3 Makkah geological categories

Geological structure	Area (km^2)	Area (%)
Precambrian igneous rocks	809	50.8
Wadi alluvium	770	48.4
Tripartite rocks	12	0.8

Urban growth data processing

Shapefiles of residential areas, within Makkah City, for 1990, 2010, and 2030 have been developed and integrated in a GIS project. Surface areas have been computed and compared for the three dates, and growth rates have been obtained. Spatial statistics tools, in the Arc Tool Box component of the Arc GIS software, have been performed in order to investigate the spatial pattern of Makkah sprawl. Applying GIS spatial analysis tools produces more valuable pieces of information. Measuring the compactness of a distribution provides a single value representing the dispersion of features around the center (Al-Ghamdi et al. 2012a). The available national 5-m-resolution DEM describes the rigid topography of Makkah metropolitan area. Several mountainous areas exist within Makkah City and affect the spatial urban growth location and direction. Thus, the residential areas' layers have been compared against the DEM layer

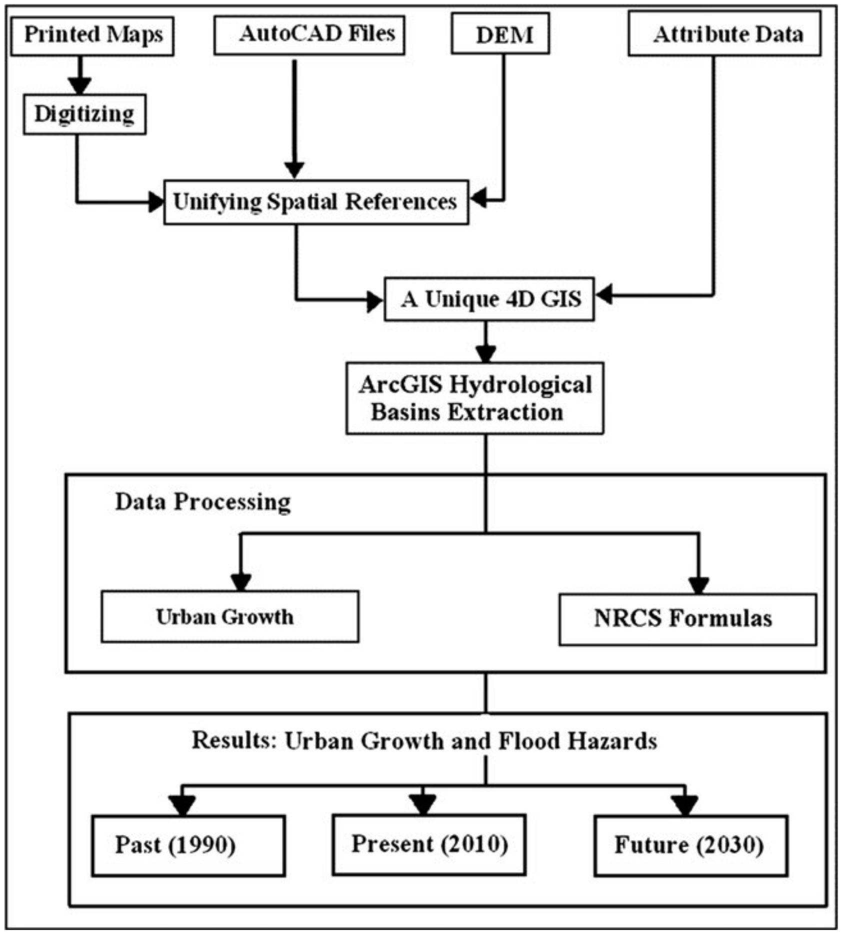

Fig. 6 The developed GIS-based flood assessment approach

in order to investigate the topography–urban development relationship. Additionally, residential areas' layers have been compared against the road network's layer in order to determine the relationship between urban growth and roads in the three scenarios under investigation. A similar task has been carried out, also, to define the relationship between urban expansion and the geology structures of the study area.

Flood data processing

First, analyzing the flood series frequency, the return period or recurrence interval can be computed. That period defines the average number of years during which a flood of a given magnitude will be equalled or exceeded once. The Welbull method, among several other formulas, computes the return period T as (Raghunath 2006):

$$T = (n+1)/m \qquad (1)$$

where n is the number of events or number of records, and m is the order or rank of the event (flood item) when flood magnitudes are ranked in descending order.

The computed return period of the 1969 flood has been estimated to be 45 years. That piece of information is quite helpful in flood assessment studies, as it means that: (a) flood magnitude is expected to occur by about 2014, and (b) the selected return period value for flood management projects should be equal or greater than 44 years. The rainfall intensity for a 50-year return period has been estimated, through the log Pearson II statistical method, as 200 mm/h.

The CN has been determined for each sub-basin in each scenario (1990, 2010, and 2030) based on the available soil and geological digital databases of Makkah metropolitan area. Dawod et al. (2011b) has performed a comparison study of several flood estimation techniques and concluded that the CN is the optimum one. Then, flood characteristics have been computed through Eq. 2, using VBA in the GIS environment. Additionally, the total flood volume of a basin is computed as:

$$QT = QA \qquad (2)$$

where Q is the depth of direct runoff (in millimeter), QT is the volume of runoff (in cubic millimeter), and A is the area of the basin (in square kilometer).

Road network data processing

Regarding flood impacts on roads, some researchers have investigated this aspect in several countries. Blanton and

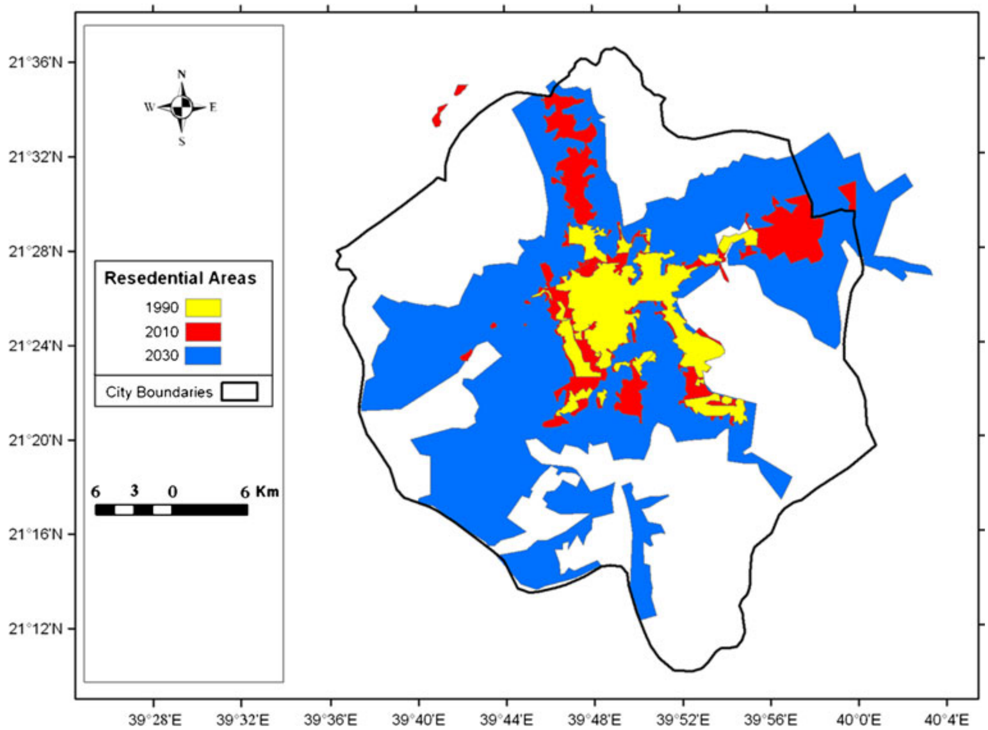

Fig. 7 Urban growth of Makkah City between 1990 and 2030

Marcus (2009) have documented the geographic distribution of roads and railroads in the alluvial floodplains of the continental USA and the regional variability of their potential impacts on lateral connectivity and resultant channel and floodplain structure and function. Youssef et al. (2010) have presented the utilization of remote sensing data, Shuttle Radar Topography Mission, coupled with geological, geomorphological, and field data in a GIS environment for the estimation of the flash flood risk along the Feiran–Katherine road, southern Sinai, Egypt. However, those two studies are based on flood hazard estimation by analyzing morphometric characteristics of basins in which roads exist. That means that the flash floods themselves have not been estimated. In the current paper, a GIS has been developed to quantify flood characteristics in Makkah City and then estimate dangerous impacts on the road network.

Next, an estimation has been developed to quantify flood impacts on roads. It is implicitly based on an idea that the higher the runoff depth in a sub-basin, the more hazards on roads within that sub-basin. Since the flood computations have been performed on a sub-basin level, the runoff depth of each sub-basin may be considered as the most effectual factor that affects the flood impact. Hence, the spatial analysis tools of the Arc GIS software are utilized to re-classify runoff depths in ten categories, and each category is assigned a unique number. That number, called the hazard, or danger, factor, will be assigned to the road existing in a particular sub-basin. By this approach, each road in the transportation network gets a unique hazard factor (in each scenario) that represents the flood hazard level.

Results and discussion

Several datasets have been compiled, processed, and analyzed in the current research study dealing with urban growth and flood hazard increase in Makkah City. The attained results can be divided in three main groups: (1) results of urbanization, (2) results of flood hazards, and (3) results of flood impacts on the road network. The results are presented in the next sections according to this classification.

Results of urban growth

For the first results' category, shapefiles of Makkah metropolitan area for 1990, 2010, and 2030 have been integrated in a GIS project (Fig. 7). Table 4 shows that the total residential area has been computed and found to be 80.012, 158.583, and 690.007 km^2 for 1990, 2010, and 2030, respectively. Thus, the residential areas in Makkah City have grown by about 98 % from 1990 to 2010 (with 4.9 % annual rate) and are expected to have grown by about 335 % from 2010 to 2030.

Table 4 Urban growth of Makkah City between 1990 and 2030

Year	Area (km^2)	Difference (km^2)	Difference (%)	Annual growth (%)
1990	80.012			
2010	158.583	78.571	98	4.9
2030	690.007	531.424	335	16.8

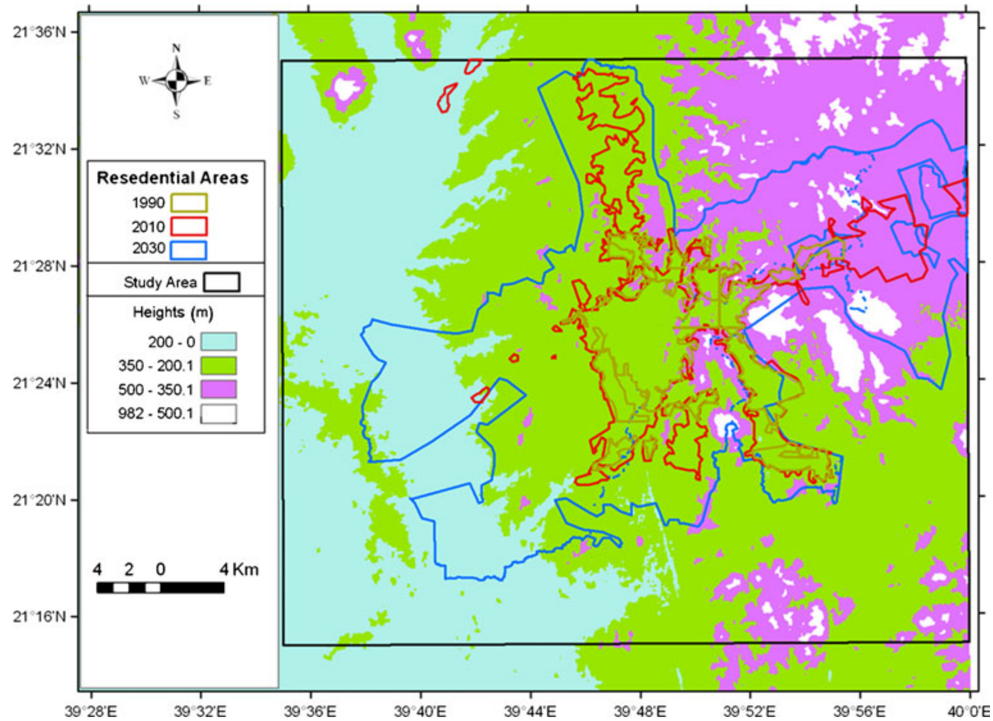

Fig. 8 Topography of residential areas in Makkah City

It can be realized from Fig. 7 that the urban growth in Makkah City takes a radial (or spoke) pattern. That is logically understood knowing that the holy mosque is considered the center of the city, and the central area around it

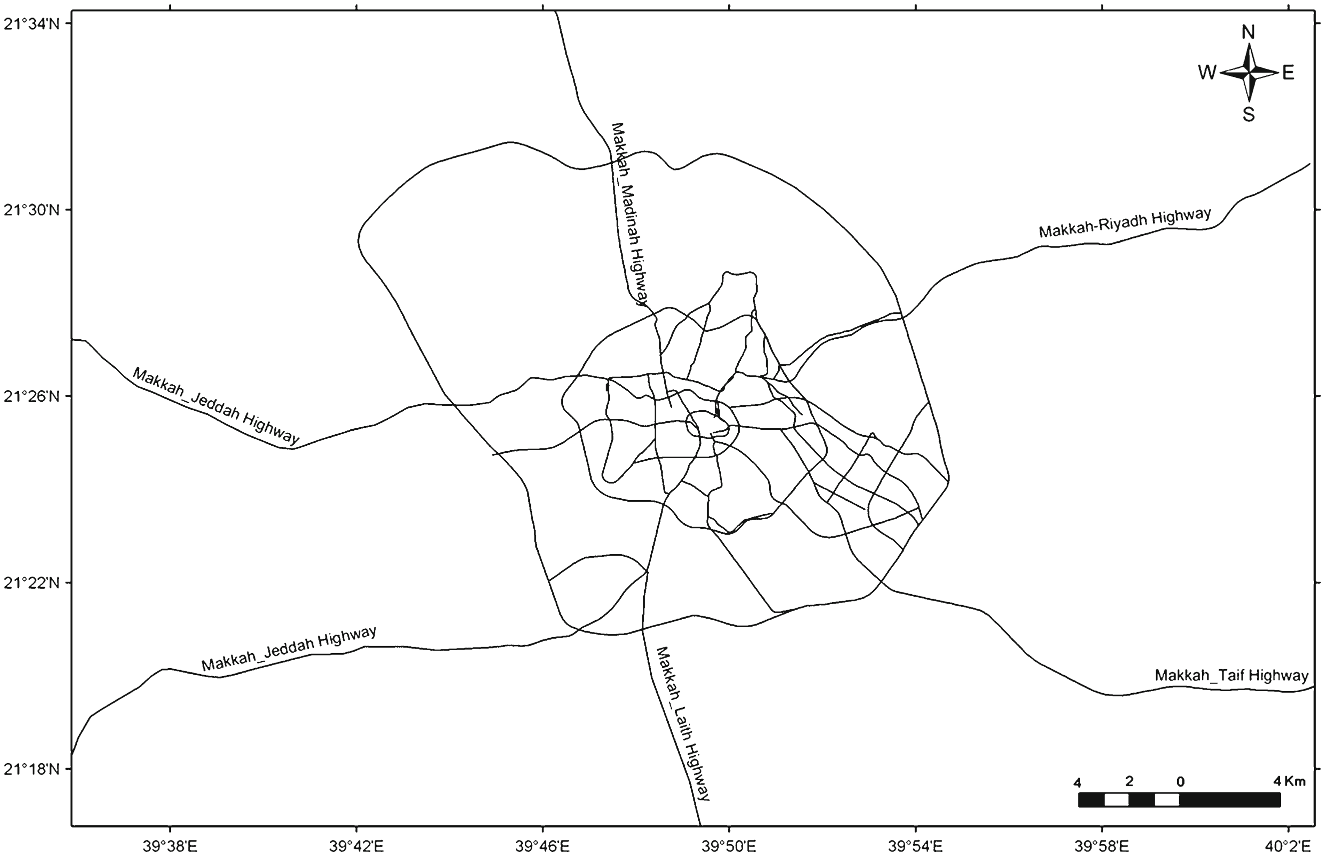

Fig. 9 Main roads in Makkah City

has the highest population density since residents and pilgrims prefer to stay close to this holy mosque.

The available national 5-m-resolution DEM describes the rigid topography of Makkah metropolitan area. Several mountainous areas exist within Makkah City and affect the spatial urban growth location and direction. Figure 8 depicts the topography of Makkah as divided into four categories. It can be seen that the urban sprawl mainly exists in low- and moderate-elevation regions. The growth spreads out along the valleys and stays away from the mountainous areas for economical reasons. It is worth mentioning that almost 50 % of Makkah's geology contains igneous rocks, mainly granite, that massively increase the development costs in mountainous areas.

Concerning the road network, it is worth mentioning that Makkah has six regional highways that connect it to a major Saudi city (Fig. 9). These roads are: Makkah–Madinah road (427 km), Makkah–Riyadh road (880 km), Makkah–Taif road (88 km), Makkah–Laith road (180 km), and two Makkah–Jeddah roads (78 km). Inspecting both Figs. 7 and 9, it can be concluded that the urban sprawl of Makkah City follows those regional roads. In the first phase (1990–210), urban development has been intensive mostly along Makkah–Riyadh and Makkah–Madinah roads. That growth leads to the creation of new districts in Makkah City, such as: Sharee'h, Sharee'h Al Mojahdeen, Al Rashdia, and Al-Khadraa at the northeast corner, and Omraa, Nowaria, and Al Bohayrat at the north corner of Makkah (Fig. 10). That conclusion consents with the values of the rotation angles of the standard deviational ellipses as argued earlier.

Results of flood hazard increase

The second results' group concerns the estimation of flood hazards in Makkah City. Six main hydrological basins have been identified in the study area, with areas ranging from 74.3 to 360.6 km^2 and lengths of their main streams varying from 16.50 to 48.55 km (Fig. 11). Table 5 presents the statistics of hydrological parameters of these basins (Koshak and Dawod 2011). Sixty sub-basins have been recognized within these six basins (Fig. 12). The NRCS method has been performed for the available data of Makkah metropolitan area to compute the peak discharge value for the six basins for the 1990, 2010, and

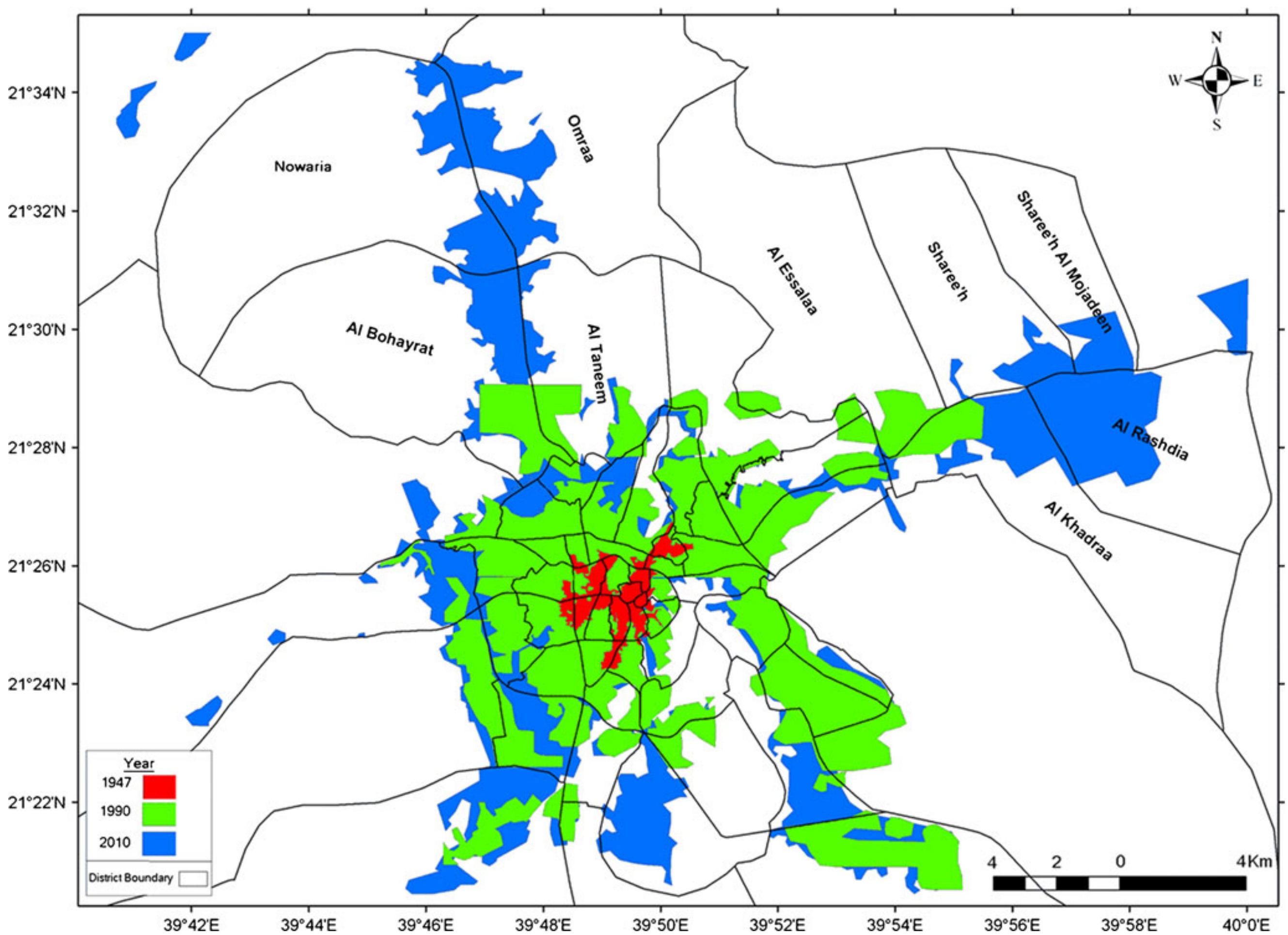

Fig. 10 New districts within Makkah City

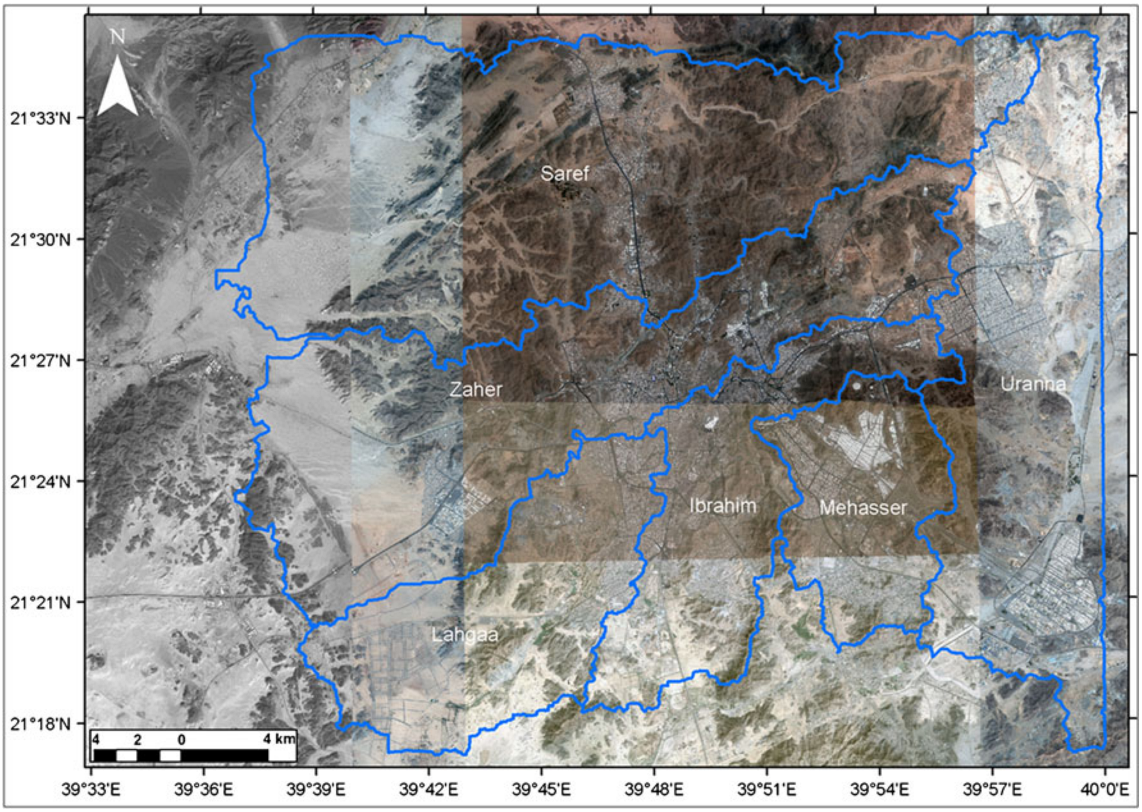

Fig. 11 The main basins in the Makkah metropolitan area

2030 datasets. The return period has been chosen, herein, as 50 years, for which the rainfall intensity has been estimated, by applying the log Pearson III statistical analysis, as 200 mm/h. The total flood volumes have been computed on the sub-basin scale, only for those sub-basins which contain residential areas. A total of 76 sub-basins, which include residential areas in 1990, have been identified within the study area. These sub-basins extended over an area of 194.726 km^2, which constitutes 17.5 % of the total area of the main hydrological basins in the study area. In 2010, the urban areas have been extended to cover 136 sub-basins, whose total areas equal 400.551 km^2. In 2030, it is expected that the urban extent of Makkah City will cover 264 sub-basins with an overall area of 780.388 km^2.

Regarding the runoff depth over the urban sub-basins, it has been found that its mean value has been increased from 165.3 mm in 1990 to 185.7 mm in 2030 (Figs. 13, 14, and 15). However, the most dangerous flood impact is the total flood volume (Figs. 16, 17, and 18). It has been found that the total flood volume (for urban sub-basins) equals 31.6, 64.6, and 141.9 million m^3 for 1990, 2010, and 2030, respectively. Hence, it is concluded that the augmentation of the total flood volume has been increased by almost 104 % from 1990 to 2010, and by almost 120 % from 2010 to 2030.

Table 5 Statistics of floods over residential areas in 1990 and 2010

Item	1990	2010	2030
Number of sub-basins containing residential areas	76	136	264
Total area of sub-basins of residential areas (km^2)	194.725	400.551	780.388
Percentage of these sub-basins' area to main basins' area	17.5 %	36.0 %	70.2 %
Minimum CN of these sub-basins	76	76	76
Maximum CN of these sub-basins	98	98	98
Mean CN of these sub-basins	88.5	88.5	95.3
Minimum runoff depth of these sub-basins (mm)	122.3	128.1	128.1
Maximum runoff depth of these sub-basins (mm)	193.9	193.9	193.9
Mean runoff depth of these sub-basins (mm)	165.3	165.3	185.7
Total flood volumes in these sub-basins (million m^3)	31.632	64.620	141.945

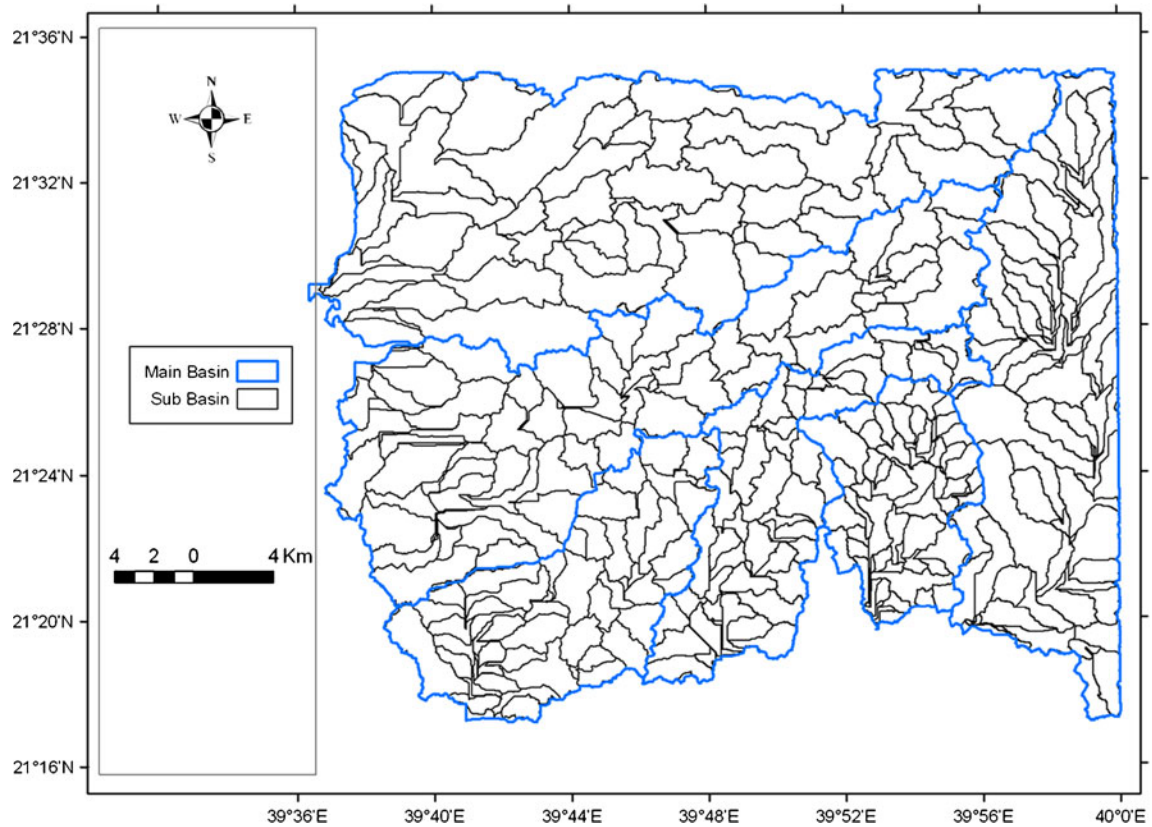

Fig. 12 The sub-basins in the Makkah metropolitan area

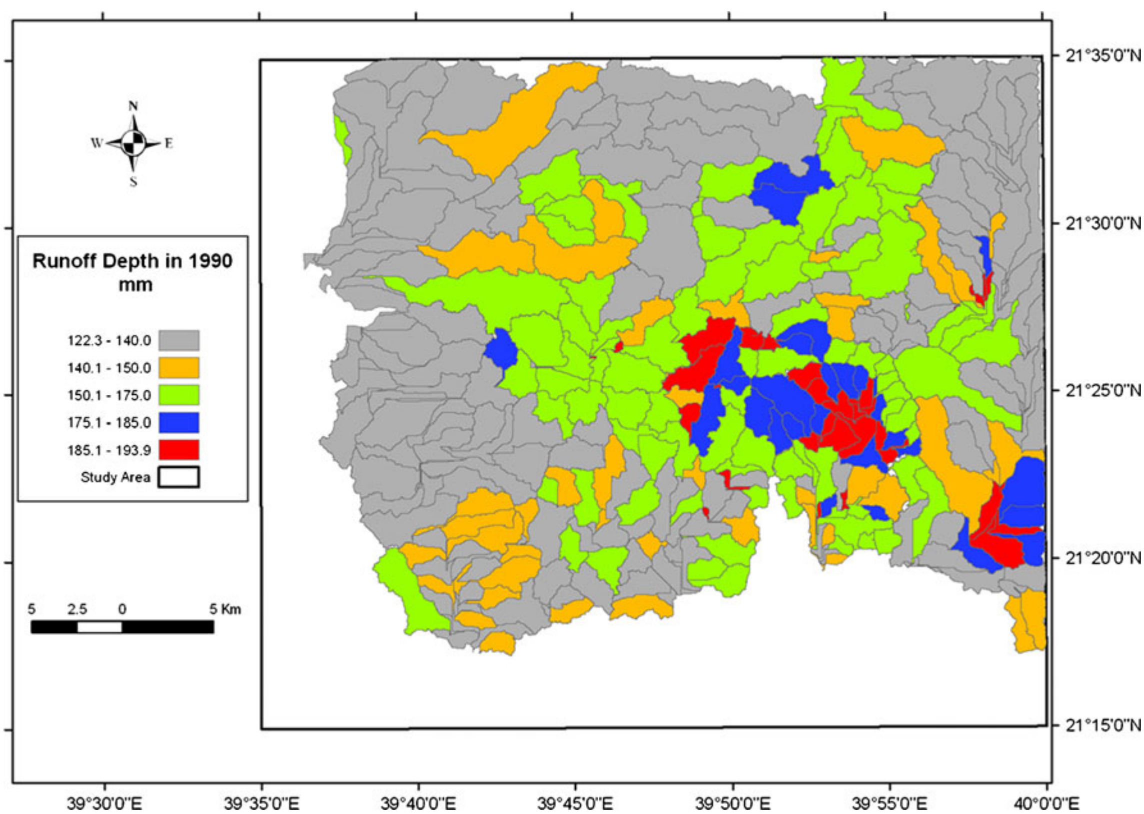

Fig. 13 Runoff depth in 1990

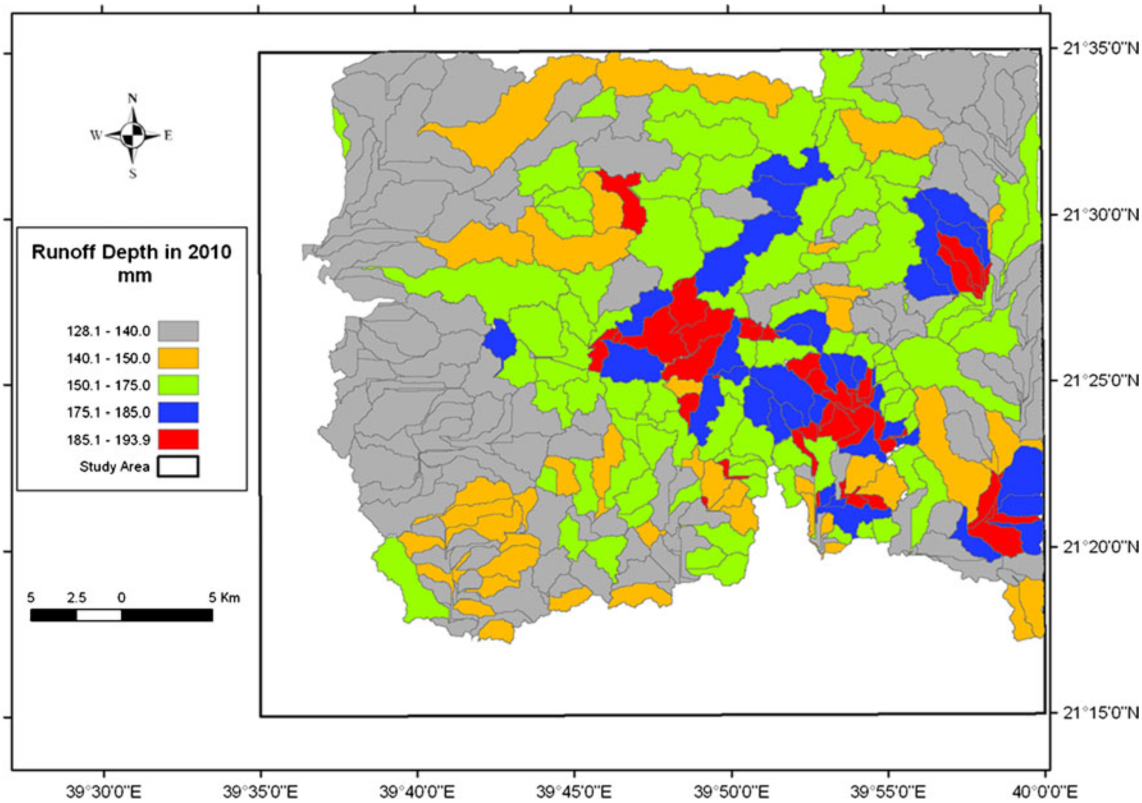

Fig. 14 Runoff depth in 2010

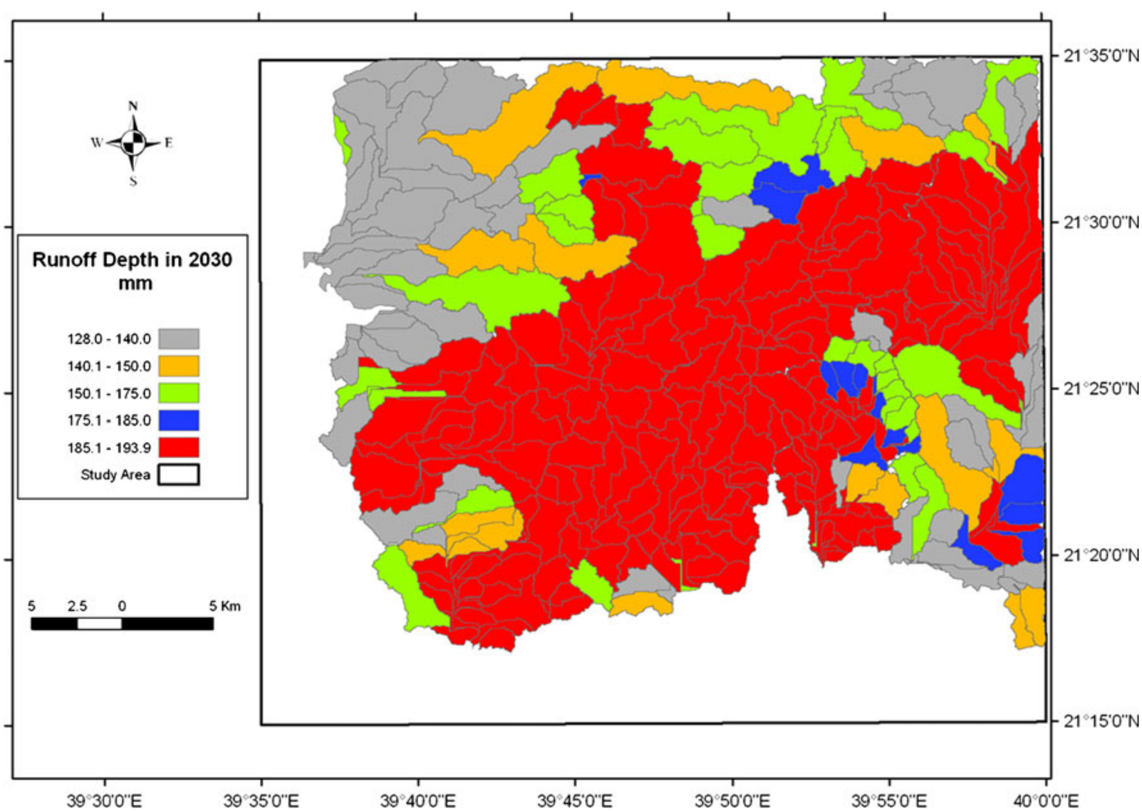

Fig. 15 Runoff depth in 2030

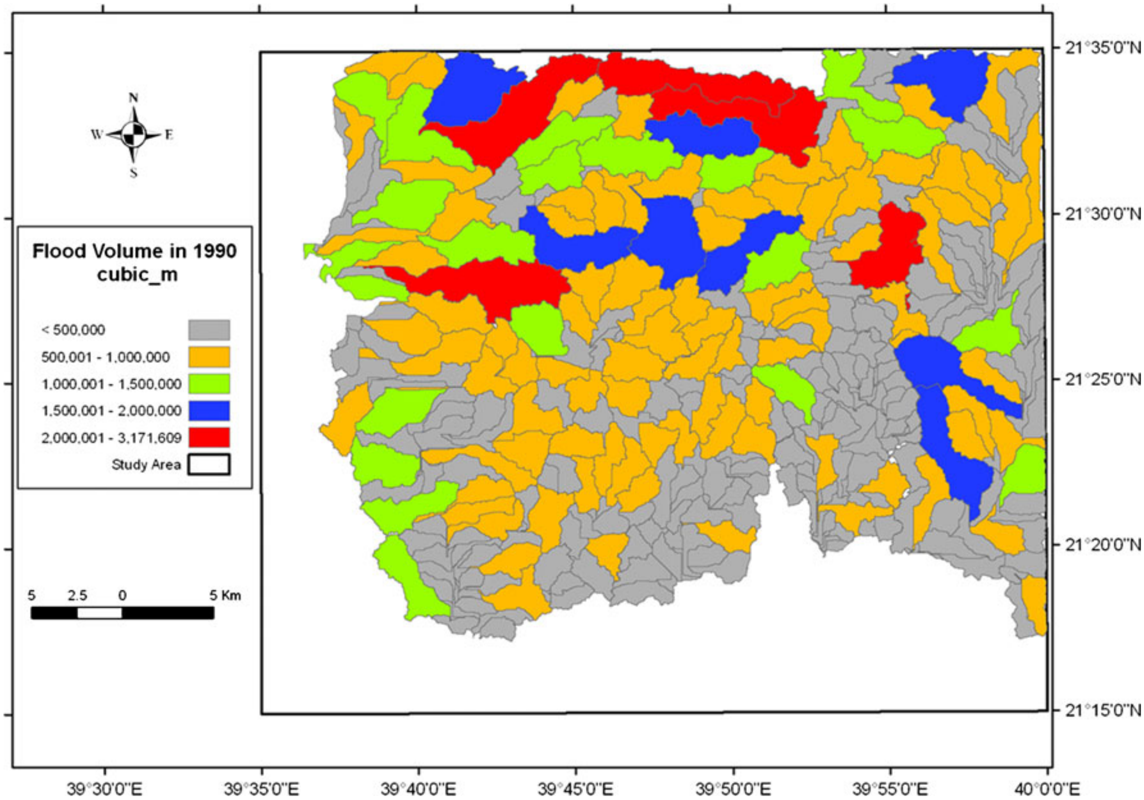

Fig. 16 Flood volume in 1990

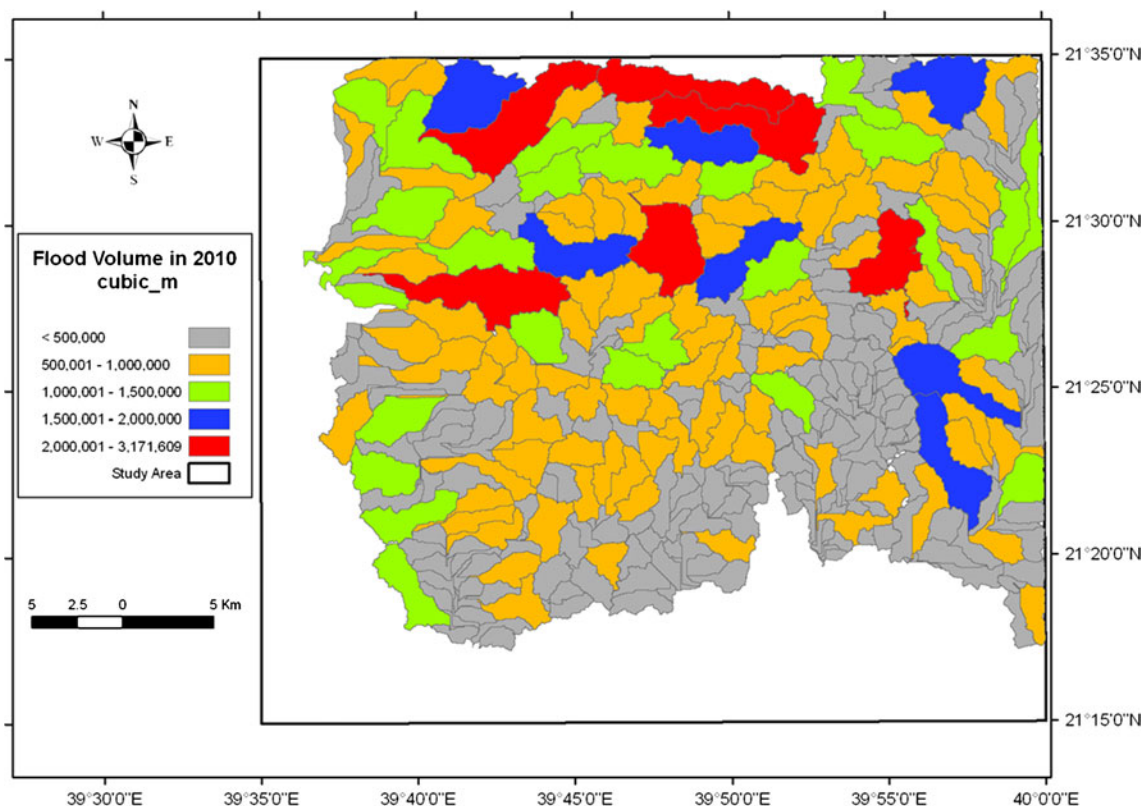

Fig. 17 Flood volume in 2010

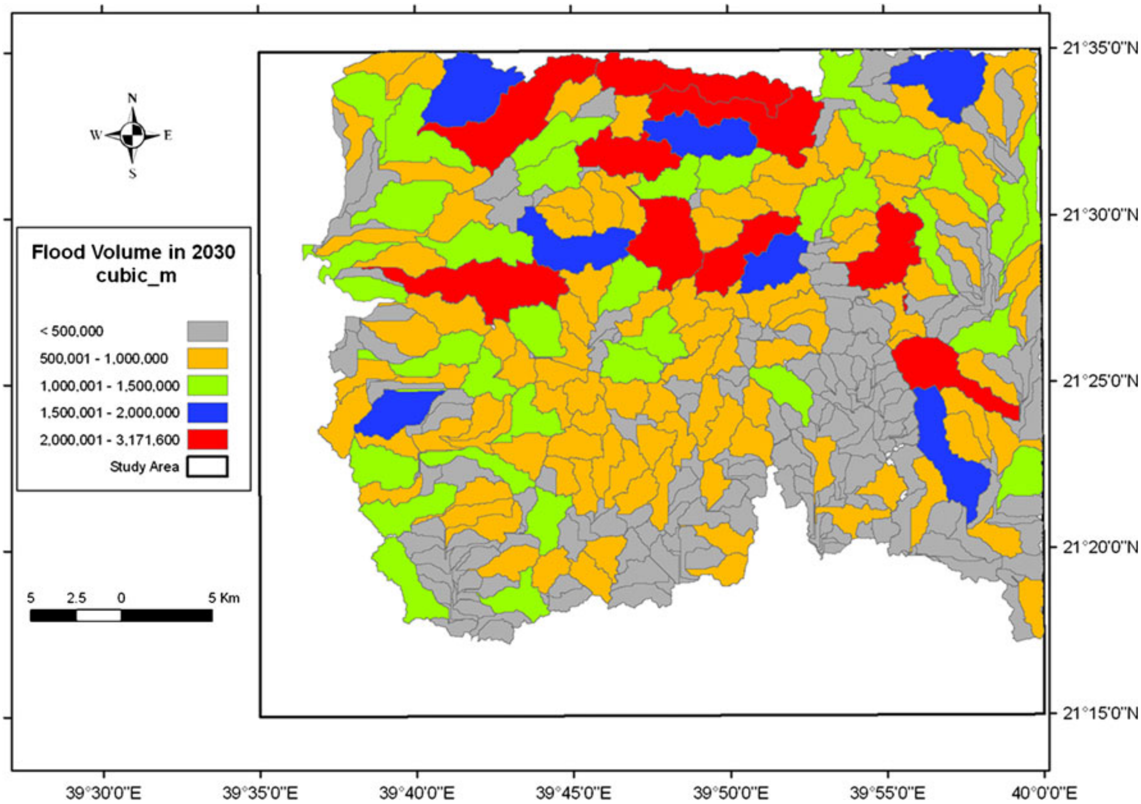

Fig. 18 Flood volume in 2030

Results of flood impacts on road network

Regarding the flood impacts on roads, two shapefiles have been constructed containing the road network of Makkah City in 2010 and 2030. It was decided to work with main roads only, whose lengths are greater than 1,000 m, just for simplicity in the current research. So, that road network, in 2010, consists of 566 roads whose lengths range from 1.004 to 20.531 km, with a mean of 2.311 km. The Arc GIS spatial analysis tools have been utilized to: (a) divide the sub-basins' runoff depth into ten groups using the equal-interval classification method; (b) re-classify those flood depth groups to unique label values ranging from 1 to 10, just for simplicity, which will be considered as the hazard factor; (c) convert that shapefile into a raster format; and (d) project that raster onto the road network in order to assign each road with the corresponding unique hazard factor. By this approach, the flood hazard impact on each road is assigned on a scale from 1 to 10 (based on the runoff depth for the corresponding sub-basin), which is a simple scale to be interpreted. This quantitative classification is presented in Table 6 and depicted in Fig. 19. Next, the flood hazards on roads have been classified into three groups, just for simplicity too, as seen in Table 6 and Fig. 20. Obviously, a great part of the road network in Makkah City is subjected to high dangerous flood impacts. That category constitutes 211 roads, representing 37 % of the network, with a total length of 481 km. It is worth noticing that roads of high flood impacts exist in the holy shrines particularly in the Arafat area. That finding is quite important and strongly necessitates the development of a specific surface water drainage network in this area to avoid flood hazards during the Hajj season.

Secondly, the same procedures have been performed on the future road networks of Makkah City in 2030. Again, it was

Table 6 Categories of flood hazard on road network in Makkah City in 2010

Hazard category	Hazard factor	No. of roads	Total length of roads (km)	Percentage of road length
Low	1–4	171	429.242	32.8 %
Medium	5–7	184	397.79	30.4 %
High	8–10	211	481.226	36.8 %

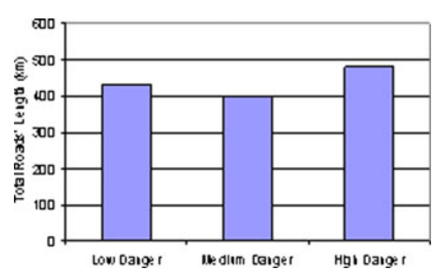

Fig. 19 Flood hazard categories on road network in Makkah City in 2010

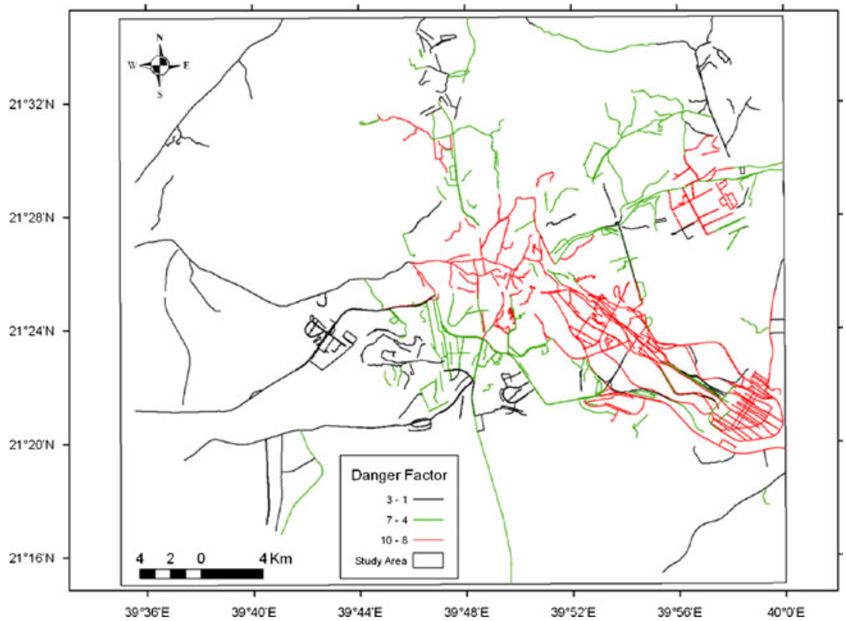

Fig. 20 Flood hazards on road network in Makkah City in 2010

decided to work with main roads only, whose lengths are greater than 1,000 m, just for simplicity in the current research. That road network consists of 705 roads whose lengths range from 1.004 to 23.70 km, with a mean of 2.691 km. The attained quantities of danger factor on roads are presented in Table 7 and depicted in Fig. 21. Additionally, the flood hazards on roads have been classified into three groups, as seen in Table 7 and Fig. 22. It is concluded that a major part of the road network in Makkah City, in 2030, is subjected to high dangerous flood impacts. That category constitutes 563 roads, representing 74 % of the network, with a total length of 1,398 km. Again, it is noticed that roads of high flood impacts exist in the holy shrines particularly in the Arafat area. That finding is quite important and strongly necessitates the development of a specific surface water drainage network in this area to avoid flood hazards during the Hajj season.

Comparing Tables 6 and 7, it can be noticed that there is a significant increase in the flood impacts on Makkah's road networks between 2010 and 2030. The overall length of flood danger-factor roads is increased from 481 km (with almost 37 %) to 1,398 km (with 74 % approximately). The main reason is the huge expected urban development of the city from 2010 to 2030, where the urban boundaries of Makkah will increase from 158 to 690 km^2. As a matter of fact, urbanization has a direct strong relationship with the flood hazards (Fig. 23). Urbanization leads to changing the land use of a region, changes its geological characteristics, and decreases its ability to absorb surface water which, in turn, increases the surface water runoff. Hence, it is concluded that the current surface water drainage network in Makkah City should be re-evaluated, in terms of its capacity and spatial distribution, in order to cope with the expected flood hazards in 2030.

Table 7 Categories of flood hazard on road network in Makkah City in 2030

Hazard category	Hazard factor	No. of roads	Total length of roads (km)	Percentage of road length
Low	1–4	71	271.355	14.3 %
Medium	5–7	69	228.329	12.0 %
High	8–10	563	1,397.964	73.7 %

Conclusions and recommendations

The current research study aims to: (1) identify land use types and road networks in Makkah, through recent high-resolution multi-band satellite images, and prepare corresponding digital maps; (2) perform hydrological modeling of flood characteristics in Makkah based on precise up-to-date metrological, geological, and topographic datasets; (3) build 4D geographic, topographic, geological, metrological, and hydrological digital databases for Makkah; (4) examine the relationship between land use, land cover changes, transportation network expansion, and the floods' prosperities and hazards, and (5)

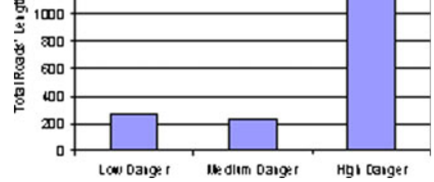

Fig. 21 Flood hazard categories on road network in Makkah City in 2030

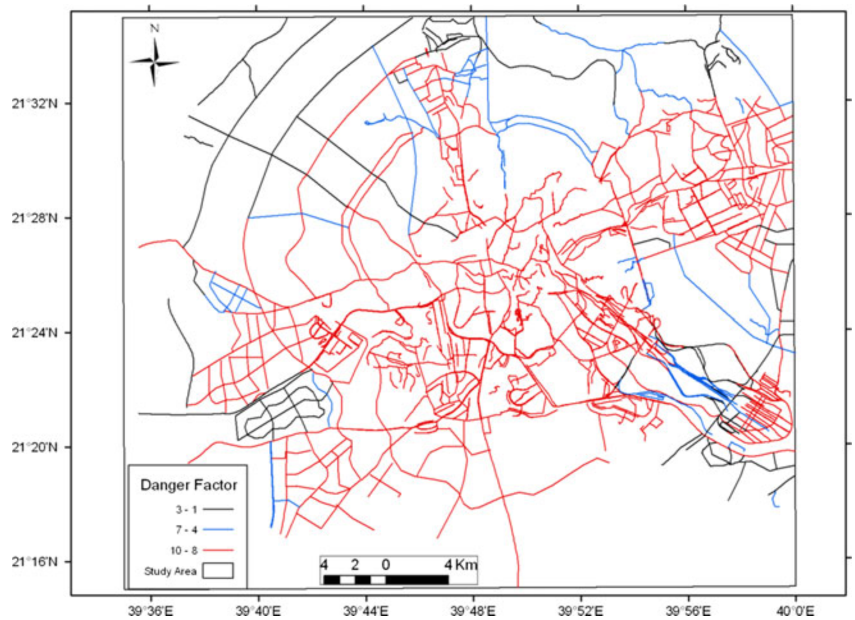

Fig. 22 Flood hazards on road network in Makkah City in 2030

develop digital hydrological maps for present and near future flood hazards in Makkah.

The main findings of the study are:

- The urban sprawl mainly exists in low- and moderate-elevation regions. The growth spreads out along the valleys and stays away from the mountainous areas for economical reasons. Almost 50 % of Makkah's geology contains igneous rocks, mainly granite, that massively increase the development costs in mountainous areas.
- Six main hydrological basins have been identified in the study area, with areas ranging from 74.3 to 360.6 km^2 and lengths of their main streams varying from 16.50 to 48.55 km. A number of 60 sub-basins have been recognized within these six basins. A total of 76 sub-basins, which include residential areas in 1990, have been identified within the study area. These sub-basins extended over an area of 194.726 km^2, which constitute 17.5 % of the total area of the main hydrological basins in the study area. In 2010, the urban areas have been extended to cover 136 sub-basins, whose total areas equal 400.551 km^2. In 2030, it is expected that the urban extent of Makkah City will cover 264 sub-basins with an overall area of 780.388 km^2.
- The mean runoff depth has been increased from 165.3 mm in 1990 to 185.7 mm in 2030. The total flood volume (for urban sub-basins) equals 31.6, 64.6, and 141.9 million m^3 for 1990, 2010, and 2030, respectively. The augmentation of the total flood volume has been increased by almost 104 % from 1990 to 2010, and by almost 120 % from 2010 to 2030.
- A great part of the road network in Makkah City is subjected to high dangerous flood impacts. That category constitutes 211 roads, representing 37 % of the network, with a total length of 481 km. Those roads of high flood impacts exist in the holy shrines particularly in the Arafat area. The future road network of Makkah City in 2030 consists of 705 roads whose lengths range from 1.004 to 23.70 km, with a mean of 2.691 km. A major part of the road network in Makkah City, in 2030, is subjected to high dangerous flood impacts. That category constitutes 563 roads, representing 74 % of the network, with a total length of 1,398 km.
- There is a significant increase in the flood impacts on Makkah's road networks between 2010 and 2030. The overall length of flood danger-factor roads is increased from 481 km (with almost 37 %) to 1,398 km (with 74 % approximately).
- Urbanization has a direct strong relationship with the flood hazards. Urbanization leads to change in the land use of a region, changes its geological characteristics, and decreases its ability to absorb surface water which, in turn, increases the surface water runoff.

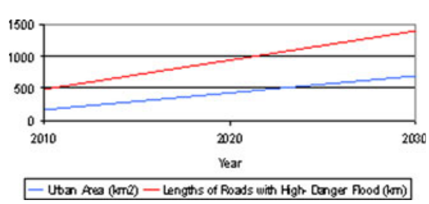

Fig. 23 Relationship between urbanization and flood impacts on roads in Makkah City

Based on the attained results, the following concluding remarks can be drawn:

– It is recommended that the attained results should be taken into account by decision makers in implementing new development planning of Makkah metropolitan area.

- The utilization of GIS in urban growth and flood hazard estimation researches is quit powerful and provides an effective technical tool which should be utilized in analyzing and understanding such phenomena.
- It is recommended that the developed flood hazard maps should be considered a chief aspect in allocating new residential areas within Makkah City.
- The current surface and flood drainage network in Makkah City should be continuously maintained and periodically cleaned, in order for them to work at maximum capacity when surface runoff starts.
- The current surface water drainage network in Makkah City should be re-evaluated, in terms of its capacity and spatial distribution, in order to cope with the expected flood hazards in 2030.
- The process of cutting mountainous portions for urbanization should be strongly controlled by decision makers, particularly during the execution stage, since some falling rocks may block the surface water drainage inlets.
- The integrated water resources management should be considered in order to optimally utilize surface and underground water resources in Makkah.
- A number of flood measurement metrological stations should be established in Makkah to measure, record, and analyze the flood characteristics more precisely.
- An on-line flood warning system should be developed in Makkah in order to issue warnings for the residents before the start of a real flood scenario.

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References

Al-Ghamdi K, Elzahrany R, Mirza M, Dawod G (2012a) Impacts of urban growth on flood hazards in Makkah City, Saudi Arabia. Int J Water Resour Environ Eng 4(2):23–34

Al-Ghamdi K, Mirza M, Elzahrany R, Dawod G (2012b) GIS evaluation of urban growth and flood hazards: a case study of Makkah City, Saudi Arabia. The International FIG Working Week 2012, Rome, Italy, May 6–10

Amini A, Ali T, Ghazali A, Aziz A, Akib S (2011) Impacts of land-use change on stream flows in the Damansara watershed. Malays Arab J Sci Eng 36:713–720

Blanton P, Marcus A (2009) Railroads, roads and lateral disconnection in the river landscapes of the continental. US Geomorphol 112:12–227

Chen J, Hill A, Urbano L (2010) A GIS-based model for urban flood inundation. J Hydrol 373:184–192

Dawod G, Mirza M, Al-Ghamdi K (2011a) GIS-based spatial mapping of flash flood hazards in Makkah City, Saudi Arabia. J Geogr Inf Syst 3(3):217–223

Dawod G, Mirza M, Al-Ghamdi K (2011b) Assessment of several flood estimation methodologies in Makkah metropolitan area, Saudi Arabia. Arab J Geosci. doi:10.1007/s12517-011-0405-5, Published online October, 6

Fred E, Mostafa B (2008) Flood risk modeling for holy sites in Makkah. Third National Conference of GIS Applications in Saudi Arabia, April 7–9, Al Khober City, Saudi Arabia

Hansford J (2010) Impact of land use changes on floods in the Upper Waikato, New Zeeland, Final Report, January 19, 16 pp

HAMDD (Higher Authority for Makkah District Development) (2004) Master planning of Makkah City till 2030. Technical report (in Arabic), Makkah. Saudi Arabia

He M, Hogue T (2011) Integrating hydrologic modeling and land use projections for evaluation of hydrologic response and regional water supply impacts in semi-arid environments. Environ Earth Sci. doi:10.1007/s12665-011-1144-3

Kar G, Kumar A, Singh R (2009) Spatial distribution of soil hydro-physical properties and morphometric analysis of a rainfed watershed as a tool for sustainable land use planning. Agr Water Manage 96:1449–1459

Koshak N, Dawod G (2011) A GIS morphometric analysis of hydrological basins for flood management within Makkah Metropolitan Area, Saudi Arabia, under review. Int J Geomatics Geosci 2 (2):544–554

Paquier A (2010) Flood studies and effects of climate changes: two examples. Presented in the International Workshop on Impacts of Global Warming from Hydrological and Hydraulics Issues, Kyoto, Japan

Mirza M, Ahmed B (2001) Winter weather and climate conditions in Makkah (in Arabic), Geographic Messages, 253, Kuwait Geographic Association, Kuwait

Mirza M (2009) Impacts of development on spatial variations in Makkah City, Saudi Arabia (in Arabic). Presented in the Fourth Arab Geographers Meeting, Rebate, Morocco

Mirza M, Dawod G, Al-Ghamdi K (2011a) Assessment of flood hazards on road network in Makkah City and holy areas using a 3D GIS (in Arabic). Unpublished technical report, Center of Research Excellence in Hajj and Omrah, Umm Al-Qura University, Makkah, Saudi Arabia

Mirza M, Dawod G, Al-Ghamdi K (2011b) Accuracy and relevance of digital elevation models for geomatics applications—a case study of Makkah municipality, Saudi Arabia. Int J Geomatics Geosci 1 (4):803–812

Mirza M, Dawod G, Al-Ghamdi K, Elzahrany R, Al-Harbi K, Shehata A (2011) Assessment of flood hazards on road network in Makkah City and holy areas using a 3D GIS. Unpublished technical report, Center of Research Excellence in Hajj and Omrah, Umm Al-Qura University, Makkah, Saudi Arabia

Mojaddadi H, Habibnejad M, Solaimani K, Abmadi M, Hadian-Amri M (2009) An investigation of efficiency of outlet runoff assessment models: Navroud watershed, Iran. J Appl Sci 9(1):105–112

Olang L, Furst J (2011) Effects of land cover change on flood peak discharges and runoff volumes: model estimates for the Nyando river basin, Kenya. Hydrol Process 25:80–89

Ragunath H (2006) Hydrology: principles, analysis, and design, 2nd edn. New Age International Limited Publications, New Delhi, India

Sheng J, Wilson J (2009) Watershed urbanization and changing flood behavior across the Los Angeles metropolitan region. Nat Hazards 48:41–57

Sherief Y (2008) Flash floods and their effects on the development in El-Qaa plain area in south Sinai, Egypt. PhD dissertation, University of Mainz, Germany

Subyani A, Qari M, Matsah M (2012) Digital elevation model and multivariate statistical analysis of morphometric parameters of some wadis, western Saudi Arabia. Arab J Geosci 5:147–157

Versini P, Gaume E, Andrieu H (2010) Application of a distributed hydrological model to the design of a road inundation warning system for flash flood prone areas. Nat Hazard Earth Syst Sci 10:805–817

Youssef A, Pradhan B, Hassan A (2010) Flash flood risk estimation along the St. Katherine road, southern Sinai, Egypt using GIS based morphometry and satellite imagery. Environ Earth Sci. doi:10.1007/s12665-010-0551-1

Wang L, Wehrly K, Breck J, Kraft L (2010) Landscape-based assessment of human disturbance for Michigan lakes. J Environ Manag 46:471–483