GIS EVALUATION OF URBAN GROWTH AND FLOOD HAZARDS: A CASE STUDY OF MAKKAH CITY, SAUDI ARABIA

Khalid A. AL-GHAMDI, Meraj N. MIRZA, , Ramze A. ELZAHRANY Saudi Arabia, and Gomaa M. DAWOD, Egypt

SUMMARY

Four-dimensional Geographic Information System (4D GIS) furnishes a noteworthy technical tool for precisely mapping 3D-space growth of urban municipality over time. It can be augmented to estimate flood hazardous impacts due to urban sprawl. In the current study, a 4D GIS has been developed to analyze and quantify both urban growth and flood hazard changes in Makkah city, Saudi Arabia, over the last twenty years. It has been found that the urban growth in 1990 took the north-east and south-west directions, while it took the north-west and south-east directions in 2010. Additionally, investigating the city topography reveals that the urban sprawl mostly exist in low- and moderate-elevation regions. Attained results showed, also, that the residential regions of Makkah city have been increased by 197%, while the total flood volumes have been enlarged by 248%. This is due to two factors: (1) establishment of new residential areas in regions that already posse high flood impacts; and (2) building up new suburban areas on sediment soil that significantly decreases the permeability of the soil and, thus, leads to a crucial increase in hazardous water surface runoff. It is concluded that the utilization of GIS in urban growth and flood hazard estimation studies is quit powerful and provides a successful technical tool that helps in analyzing and understanding such phenomena. It is recommended that the achieved findings should be taken into account by decision-makers in development planning and resources management policies for Makkah metropolitan area.

Keywords: GIS, Spatial analysis, Urban growth, Flood hazards, Rainfall-Runoff, Saudi Arabia.

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1. INTRODUCTION

Urbanization is an outcome of natural and socio-economic factors and their utilization by man in time and space. The dispersed development along highways, or surrounding a city and in rural countryside is called urban sprawl. Geomatics technologies, such as Remote Sensing (RS) and GIS, furnish exceptional technical tools for urban modelling and planning. Mapping the spatial (three-dimensional) growth of a city over time, i.e. a four-dimensional scenario, is a central aspect in developing city planning strategies. Several researchers have examined this issue particularly with utilization of GIS and RS. Mishra et al. (2011) carried out a research project for detecting urban growth (1930-2005) and land use changes (2000-2005) in Bhubaneswar city, India. Also, Saravanan and Ilangovan (2010) used GIS to investigate the nature and pattern of urban expansion of Madurai city over its surrounding region during the period 1991-2006. Similarly, Feng (2009) used GIS and RS to quantifying the urban sprawl in China over the period 1980-2003. Moreover, Alabi (2009) integrated RS and GIS data to examine the sprawl of Lokoja region, Nigeria over the period 1987-2007. Abd-Allah (2007) utilized GIS and RS in modelling urban dynamics, particularly for quantifying the loss in agricultural lands in the greater Cairo region, Egypt, for 1972-2005.

On the other hand, floods are natural returning hydrological phenomena that affect human lives. Hazards of flash floods, chiefly in urban regions, are vital from both human settlement and economical perspectives. Recently, the estimation of flood hazardous impacts and the development of GIS-based flood inundation maps have been considered a crucial demand. For example, Sagala (2006) carried out a detailed vulnerability assessment study to investigate physical flood hazards, particularly buildings' damages, in a residential area depending upon a mobile GIS. Fernandez and Lutz (2010) described a GIS-based research produced flood hazard maps for two cities in Argentina based on a multi-criteria design analysis. Park and Hur (2011) have utilized GIS for the development of flood simulation system for Namgang watershed, Korea. In addition, a similar methodology was proposed and rested in Georgia, USA (Qi and Altinakar, 2011). Hagen et al. (2011) presented a simple methodology for developing a nation-wide flood hazard maps in Afghanistan as an example of developing countries.

A special attention was given to the interrelationship between urbanization and flood hazardous impact in the last few decades. He and Hogue (2011) integrated hydrologic modelling and land use projections to predict long-term impacts of urbanization on hydrologic behavior and water supply in Los Angeles, USA. Amini et al. (2011) concluded that changes in land-use will increase the peak stream flow, and the increase is directly proportional to the rate of urbanization in Damansara watershed, Malaysia. Additionally, Zheng and Qi (2011) highlighted that serious natural hazards, particularly flood impacts, are increased due to urbanization in Chinese mountainous cities. 3D GIS models are proposed for simulating flood spreading in urban areas in order to decide optimum urban protection levels (e.g. Wang et al., 2010, and Merwade et al., 2008). Moreover, GIS was used for assessing economic impacts of flood damages in Korea (Yi et al., 2010) and in France (Vinet 2008).

In Kingdom of Saudi Arabia (KSA), GIS and RS have been utilized in a variety of planning and development tasks such as: urban-rural land use change detection (e.g. Belaid, 2003), change detection in coastal areas (e.g. Al-Otaibi et al., 2006), traffic planning in Makkah city (Koshak 2006), modelling urban growth dynamics (e.g. Al-Ahmadia et al., 2008), analysis of population distribution variations (Elzahrany 2007), developing maps from RS images (AlSultan et al., 2008), groundwater exploration (e.g. El-Hames et al., 2001, and Al Saud 2010), and morphometric analysis (Subyani et al., 2010). Moreover, a great attention has been paid recently to the issue of flood assessment and flood hazards estimation in KSA. For example, Dawod et al. (2011) developed a GIS-based process to quantify the flood parameters, e.g. peak discharge and runoff volume, in Makkah city based on the US National Resources Conservation Service (NRCS)'s flood modelling method (known also as the curve number methodology). Moreover, Subyani (2011) investigated the flood probability for arid basins in Makkah administrative area. Dawod and Koshak (2011) developed NRCS-based unit hydrographs for the six catchments within Makkah metropolitan area as a tool for rainfall-runoff modelling and flood management. This paper aims to monitor and quantify the spatial urban sprawl of Makkah metropolitan area and the anticipated flood hazards' increase over the period 1947-2010 within a GIS environment.

2. STUDY AREA

Makkah city is located in the south-west part of Kingdom of Saudi Arabia (KSA), about 80 km east of the Red Sea (Fig. 1). It extends from longitudes 39^{o} 35’ E to 40^{o} 02’ E, and from latitudes 21^{o} 09’ N to 21^{o} 37’ N. The current area of the metropolitan region (the study area) equals 1593 square kilometres. Makkah city is a unique city for Muslims all over the world, since it contains the holly 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 Muslims are gathered in Makkah yearly. Also, Muslims prefer to perform a religious tourism plane, called Omarh, to Makkah all over the years. This is an important factor to be considered in analyzing the urban growth of this city. 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.

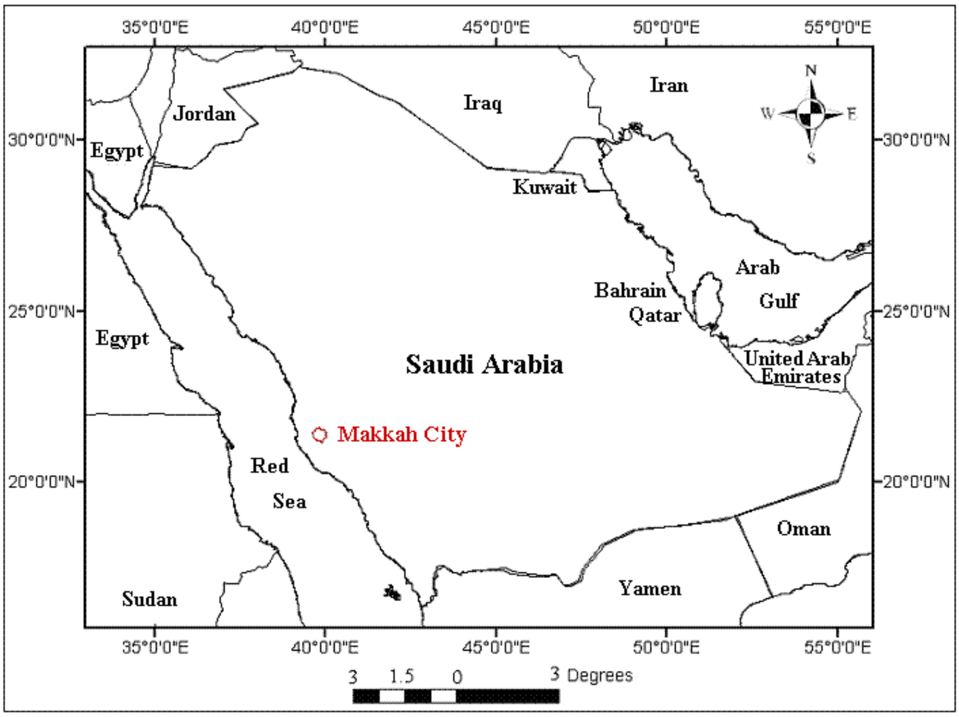


Figure 1: Study Area

On a national level, precise flood assessment is considered as an important demand in Makkah metropolitan area due to the unexpected nature of rainfall that often produce flash hazardous floods. The annual rain over Makkah city, for a period extending from 1966 to 2010, varies from 3.8 mm to 318.5 mm, with an average of rainfall equals 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) 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. The topography of the Makkah metropolitan area is complex, where several mountainous regions exist within the urban boundaries of the city. Terrain elevations in Makkah (Figure 3) range from 82 to 982 meters above sea level (Mirza et al., 2011).

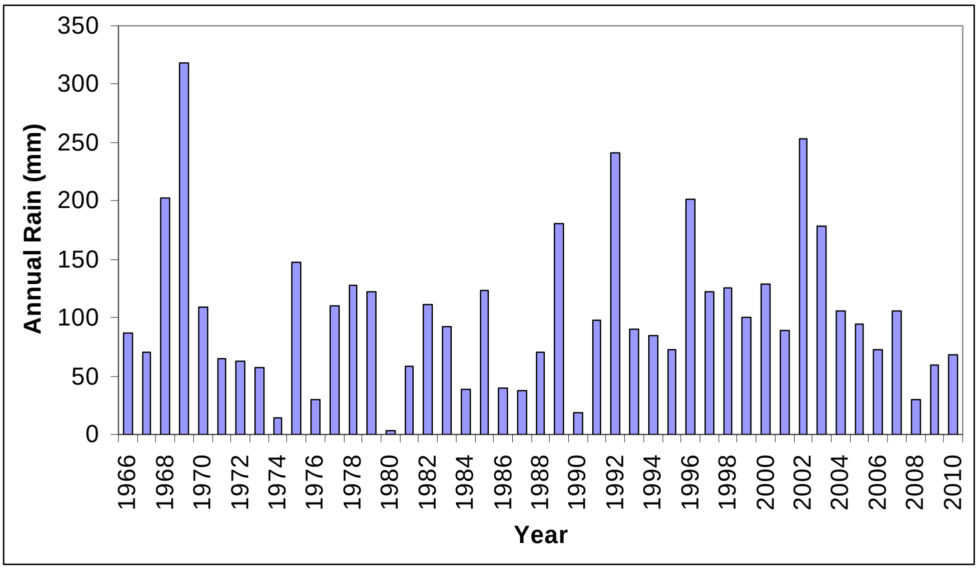


Figure 2: Annual Rains in Makkah city from 1966 to 2010

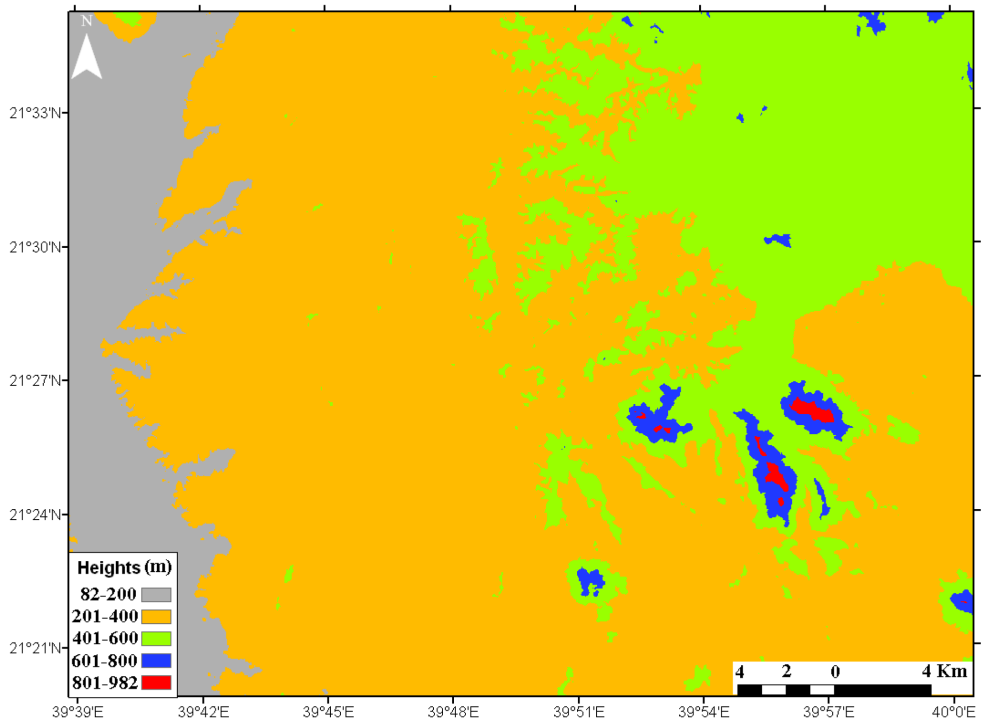


Figure 3: Elevations of Makkah city

3. DATA AND METHODOLOGY

The spatial compiled datasets constitute of three categories. The first element is a topographic map of Makkah city in 1947. The second group consists of 105 cadastral maps in AutoCAD file format for 1990. The third constituent consists of a land use map developed by the Saudi geological survey authority dated 2010. Additionally, a national 5-meter resolution Digital Elevation Model (DEM) for the study area has been obtained from King Abdulaziz City of Sciences and Technology (KACST). 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, and to delineate the main hydrological basins, and their associated sub-basins, in the study area. The processing phase includes (Fig. 4): rectifying the printed maps, digitizing two shapefile 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 analysis; and flood estimation. The term 4D GIS in Fig. 4 indicates the integration and utilization of 3D spatial datasets for several time intervals in a unique GIS environment.

Regarding flood estimation, the NRCS, formerly known as the Soil Conservation Service (SCS), has been selected in this research study since it might be considered the most widely-utilized flood modelling methodology. It utilizes geological information to assign a unique Curve Number (CN) coefficient value for each area, that will be further used to estimate the surface runoff depth and the peak discharge magnitude. The NRCS method is quit utilized in engineering design and flood management projects (e.g. Masoud, 2011, Al-Jabari et al., 2009; Adebayo et al., 2009; Elaji, 2010; Xianzhao and Jiazhu, 2008; and Gul et al., 2009), and particularly in USA (e.g. US ACE, 2004; and US DoT, 2002). The basic formulas of the NRCS approach are (e.g. US NRCS, 1986):

$$Q = (P - 0.2\ S)^2 / (P + 0.8\ S) \qquad (1)$$

where,

Q = depth of direct runoff (mm)
P = depth of precipitation for a specific return period (mm)
S = maximum potential retention (mm):

$$S = 25.4\ ((1000 / CN) - 10) \qquad (2)$$

where CN is the curve number. Tables provide values of CN are presented in several hydraulic literatures (e.g., Sen 2008b, pp. 165). Table 1 presents some of these CN values.

$$qp = qu\ A\ Q \qquad (3)$$

where,

qp = peak discharge (m^3/s)
A = drainage area (km^2)

Q = depth of runoff (mm)
qu = unit peak discharge ($m^3/s/km^2/mm$) that can be interpolated from a specific charts (e.g. US NRCS, 1986) or computed from corresponding tables (e.g. US DoT 2002, pp. 5-28).

$$Q_T = Q\ A \tag{4}$$

where Q_T = Flood volume (m^3)

Table 1: Examples of runoff CN values

Cover Type	Hydrological Soil Types			
	A	B	C	D
Fully developed urban areas (vegetation established):				
- Good condition; grass cover on 75% or more of the area	39	61	74	80
- Fair condition; grass cover on 50% to 75% of the area	49	69	79	84
- Poor condition; grass cover on 50% or less of the area	68	79	86	89
Streets and Roads:				
- Paved with curbs and storm sewers (excl. right-of-way)	98	98	98	98
- Gravel (incl. right-of-way)	76	85	89	91
Industrial districts (72% average impervious)	81	88	91	93
Commercial and business areas (85% average impervious)	89	92	94	95
Where: Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted, Group B soils have moderate infiltration rates when thoroughly wetted, Group C soils have low infiltration rates when thoroughly wetted, Group D soils have high runoff potential and low infiltration rates when thoroughly wetted.				

after US NRCS 1986.

Simply, the flood processing stage starts by assigning a CN value for each sub-basin based on its geological, soil, and land use properties. Then the maximum potential retention, S, is computed through eq. 2. The value of the depth of precipitation, P in eq. 1, is obtained through the Pearson Log III statistical analysis of the rainfall dataset for a specific return period (e.g., 50 years in the current study). The depth of runoff, Q in eq. 1, can then be computed. Next, the unit peak discharge, qu, being computed or interpolated from the corresponding specific diagrams. Finally, the peak discharge, qp, is evaluated through eq. 3, and the total flood volume for each sub-basin, Q_T, is obtained from eq. 4.

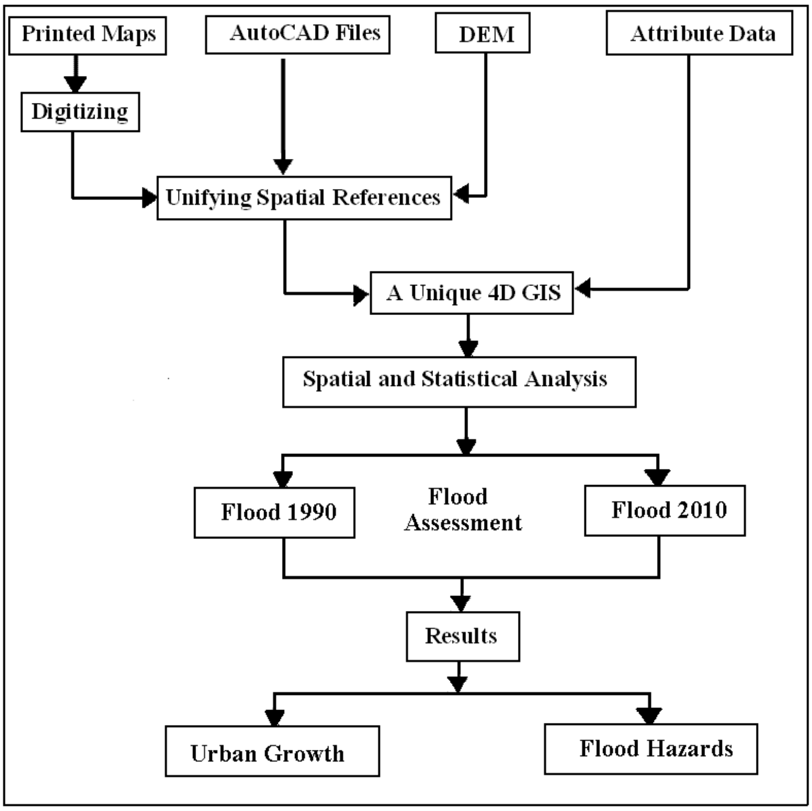


Figure 4: Processing Workflow

4. RESULTS AND DISCUSSION

The attained results may be divided into two main groups: (1) results related to urban growth; and (2) results related to flood hazards. For the first results' category, shapefiles of Makkah metropolitan area for 1947, 1990, and 2010 have been integrated in a GIS project (Fig. 5). The total residential area has been computed and found to be 5.168, 99.234, and 158.583 square kilometers for 1947, 1990, and 2010 respectively. Thus, the residential areas in Makkah city have been grown by about 1820% between 1947 and 1990 (with 42% annual rate), and by about 97 % from 1990 to 2010 (with 4.8 % annual rate). The most important reason behind the huge urban sprawl in mid 20th century might be the enormous national income expansion due to the oil exploration in the Gulf region. That economical enlargement caused an urban development revolution not just in Makkah city but almost in all towns within Saudi Arabia. Secondly, the official planning rules and governmental authority have been started in 1955 in order to regulate the urban development of Makkah city (HAMDD 2004).

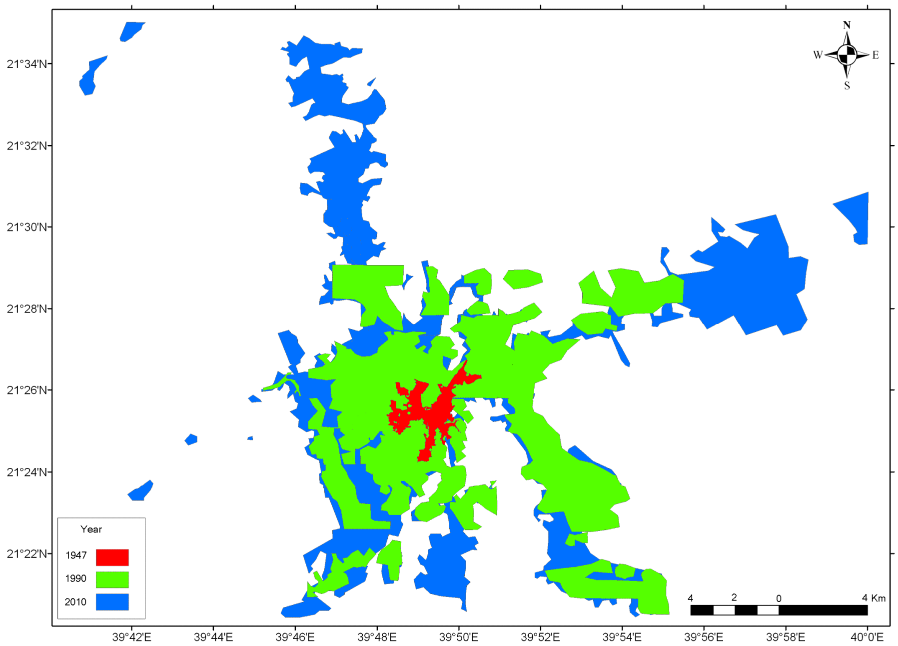


Figure 5: Urban Sprawl of Makkah City

It can be realized from figure 5 that the urban growth in Makkah city takes a radial (or spoke) pattern. That is logically understood knowing that the holly mosque is considered the center of the city, and the central area around it has the highest population density since residents and pilgrims prefer to stay close to this holly mosque.

Applying GIS spatial analysis tools produces more valuable pieces of information. The directional distribution tool supplies precious information about the spatial directional trend of the urban spread out. Directional distribution, or standard deviational ellipse, has been carried out for the three urban development stages of Makkah city (Fig. 6). Although a directional ellipse by itself gives a static perspective about the residential areas at a specific time, comparing several ellipses may give an idea about the changes took place over a time interval. The idea, herein, is that the changes occurred in the ellipses' orientation may portrait, to some extent, the variations of the residential areas' expansion or growth directions. From figure 6, it can be noticed that the azimuth of the major axes of the ellipse, in a clockwise from the North direction, has been found to be 35^{o}, 31^{o}, and 148^{o} for 1947, 1990, and 2010 respectively. Therefore, the urban growth in both 1947 and 1990 took the north-east and south-west directions, while it took the north-west and south-east directions in 2010. So, such results conclude that the growth general direction has been relatively fixed between 1947 and 1990, while it has been significantly changed between 1990 and 2010.

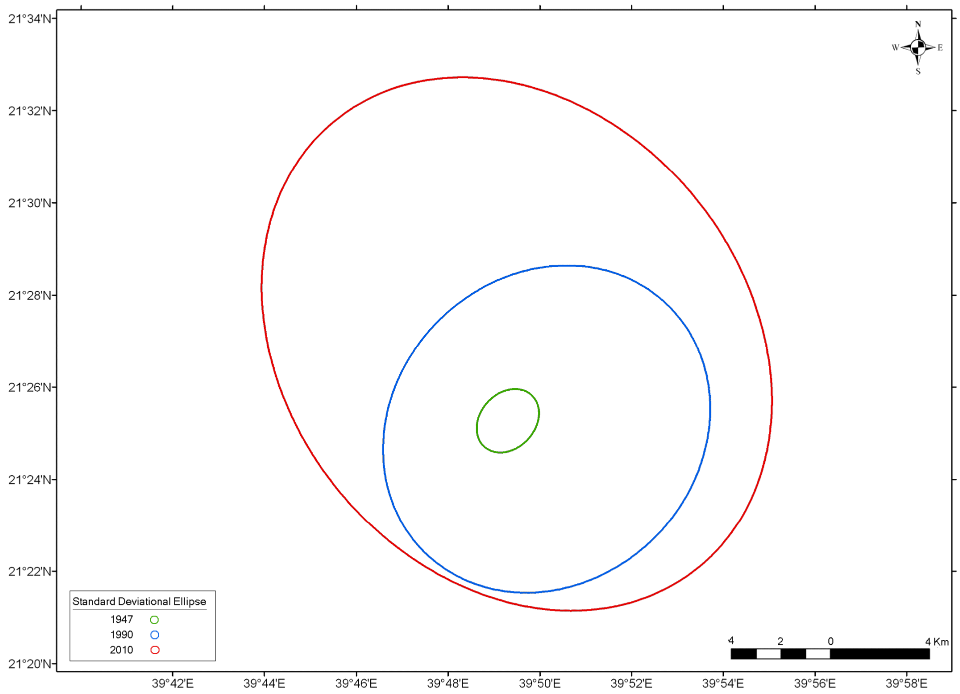


Figure 6: Standard Deviational Ellipses of Urban Sprawl of Makkah City

The available national 5-meter 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 7 depicts the topography of Makkah as divided into four categories. It can be seen that the urban sprawl mainly exist in low- and moderate-elevation regions. The growth spreads out along the valleys and stays away from the mountainous areas for economical reasons. It worth mentioning that almost 50% of Makkah's geology contains igneous rocks, mainly granite, that massively increase the development costs in mountainous areas.

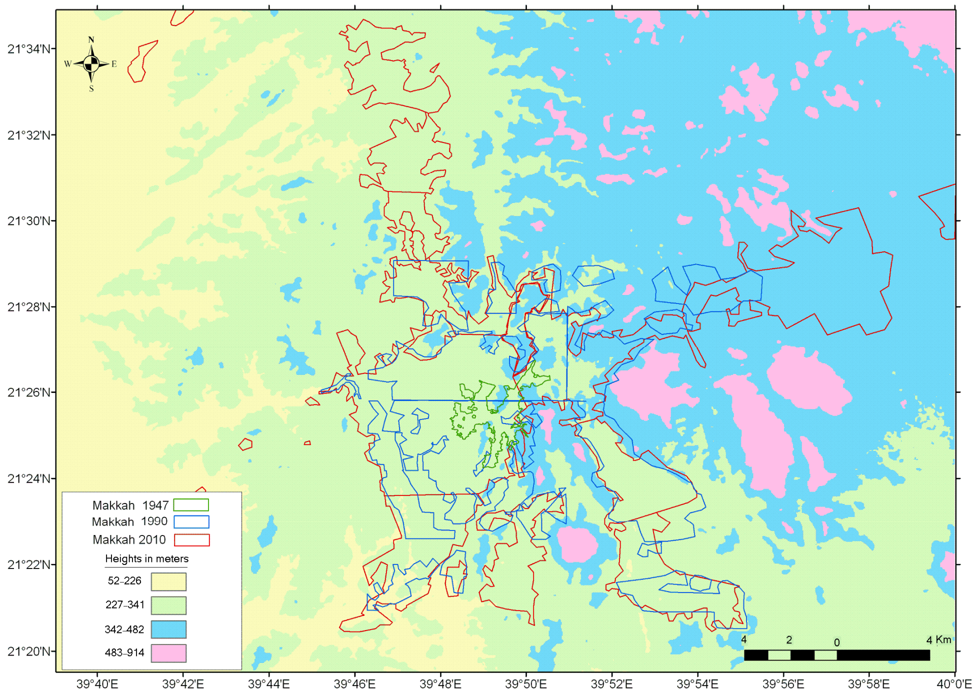


Figure 7: Topography of Residential Areas in Makkah City

Concerning the road network, it worth mention that Makkah has six regional highways that connect it to major Saudi city (Fig. 8). 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 figures 3 and 7 concludes that the urban sprawl of Makkah city follows those regional roads. In the first phase (1947-1990) the urban growth has been concentrated mainly along Makkah-Riyadh and Makkah-Taif roads. Moreover, in the second phase (1990-210) the 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 North-East corner, and Omraa, Nowaria, Al Bohayrat at the North corner of Makkah (Fig. 9). That conclusion consents with the values of the rotation angles of the standard deviational ellipses as argued earlier.

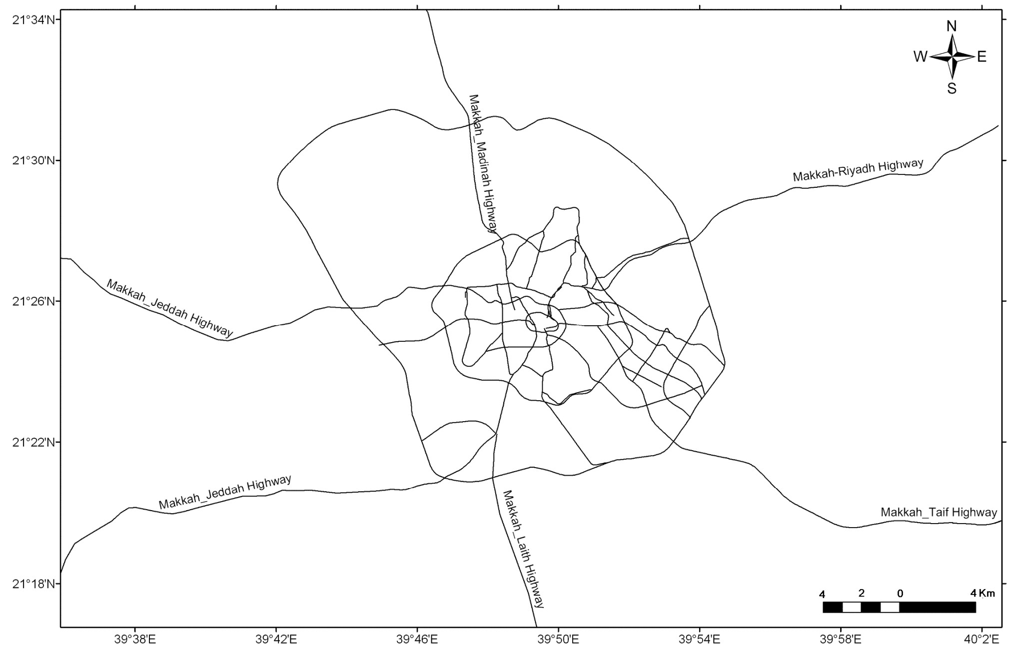


Figure 8: Main Roads in Makkah City

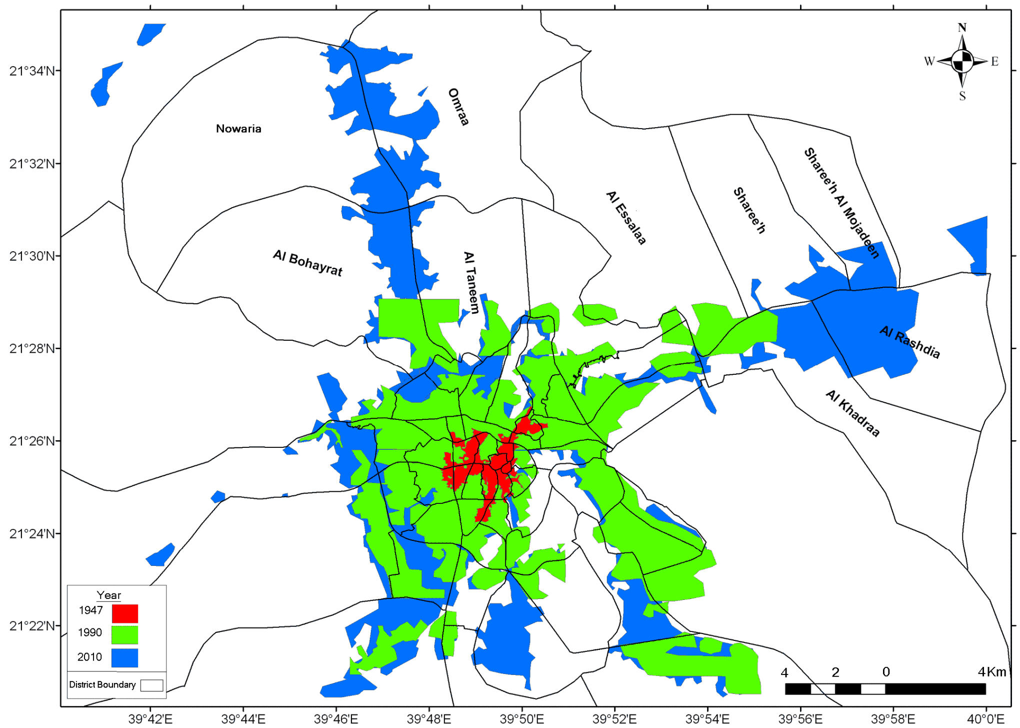
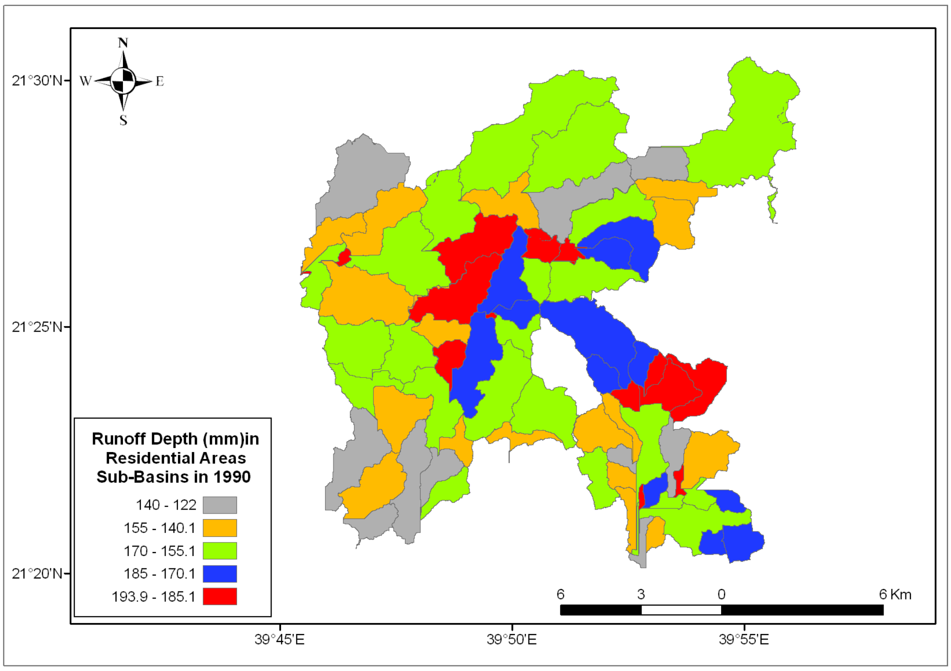


Figure 9: New Districts Within Makkah City

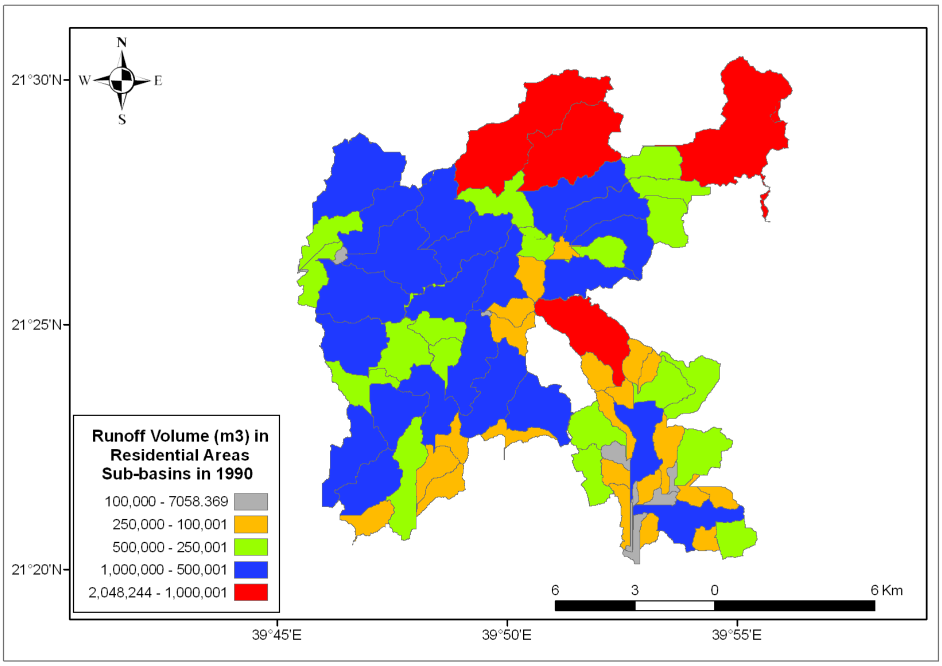
The second category of accomplished results deal with the estimation of flood hazards in Makkah city. The NRCS method has been performed for the available data of Makkah metropolitan area to compute the peak discharge value for the six basins for 1990 and 2010 datasets. The return period has been chosen, herein, as 50 years, for which the rainfall intensity (P in equation 1) has been estimated, by applying the Log Pearson III statistical analysis, as 200 mm/hour (Dawod et al., 2011). Table 2 presents statistics of the attained flood parameters, over residential areas, for 1990 and 2010. The runoff depth and the total flood volumes have been computed on the sub-basin scale, only for those sub-basins contain residential areas (Fig. 10). Twenty-five sub-basins that include residential areas, in 1990, have been identified within the study area. The area of these sub-basins range from 0.478 to 10.663 square kilometers, with a sum of 71.587 square kilometers. The flood volumes of these sub-basins have been estimated (equation 4) for 1990 and found to vary from 79.6 to 1809.7 thousands cubic meters with a total of 11849.9 thousands cubic meters. Then, utilization of the 2010 datasets revealed that there are 64 sub-basins that include residential areas (Fig. 11). The area of these sub-basins range from 0.223 to 18.569 square kilometers, with a sum of 157.564 square kilometers. The flood volumes of these sub-basins have been estimated for 2010 and found to vary from 45.5 to 2928.7 thousands cubic meters with a total of 41282.1 thousands cubic meters.

Table 2: Statistics of floods over residential areas in 1990 and 2010

Item	1990	2010
Number of sub-basins contain residential areas	25	64
Total area of residential areas (km^2)	80.021	157.564
Minimum flood volumes (m^3)	79,623	45,487
Maximum flood volumes (m^3)	1,809,701	2,928,694
Total flood volumes (m^3)	11,849,980	41,282,085

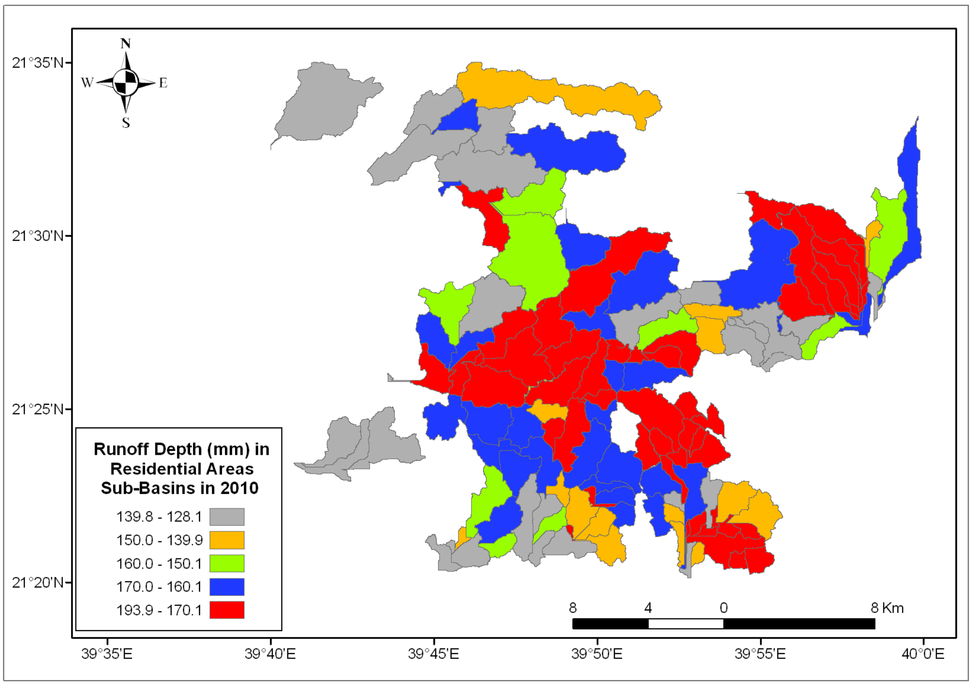


(a) Runoff Depth



(b) Flood Volume

Fig 10: Floods over Residential Areas in 1990



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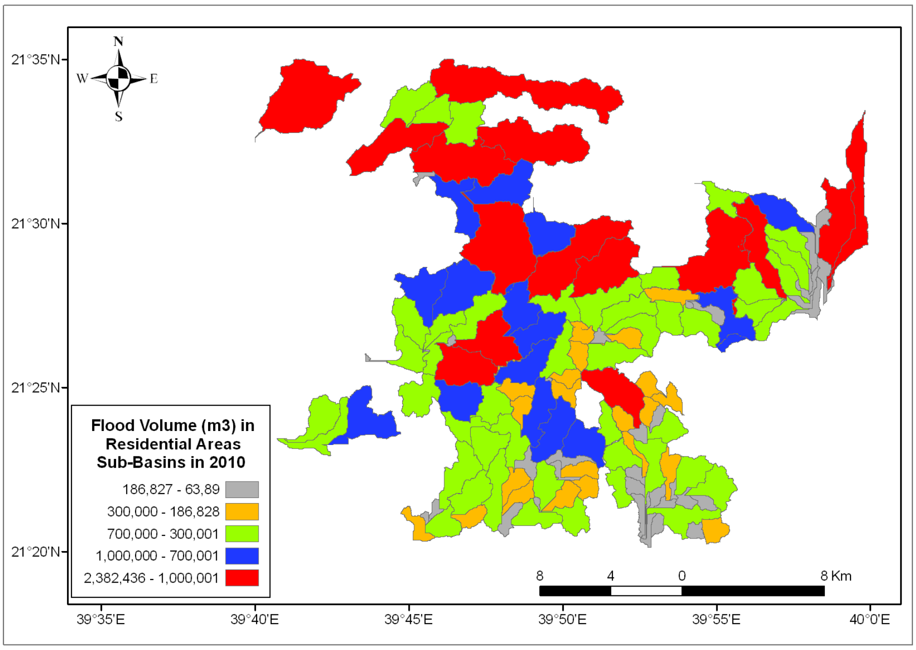
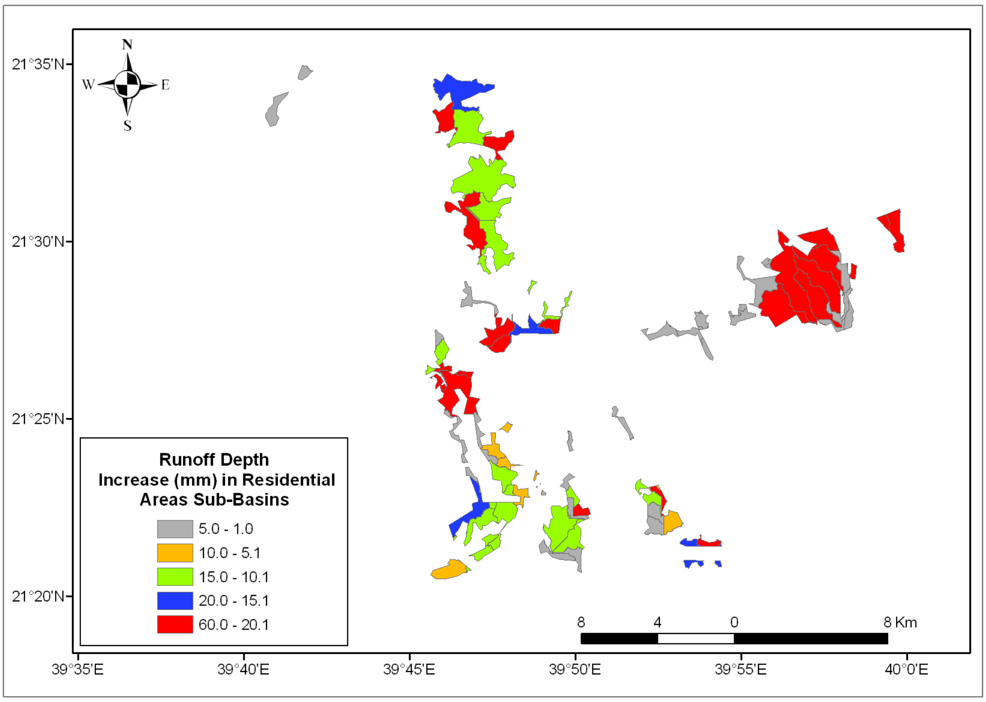


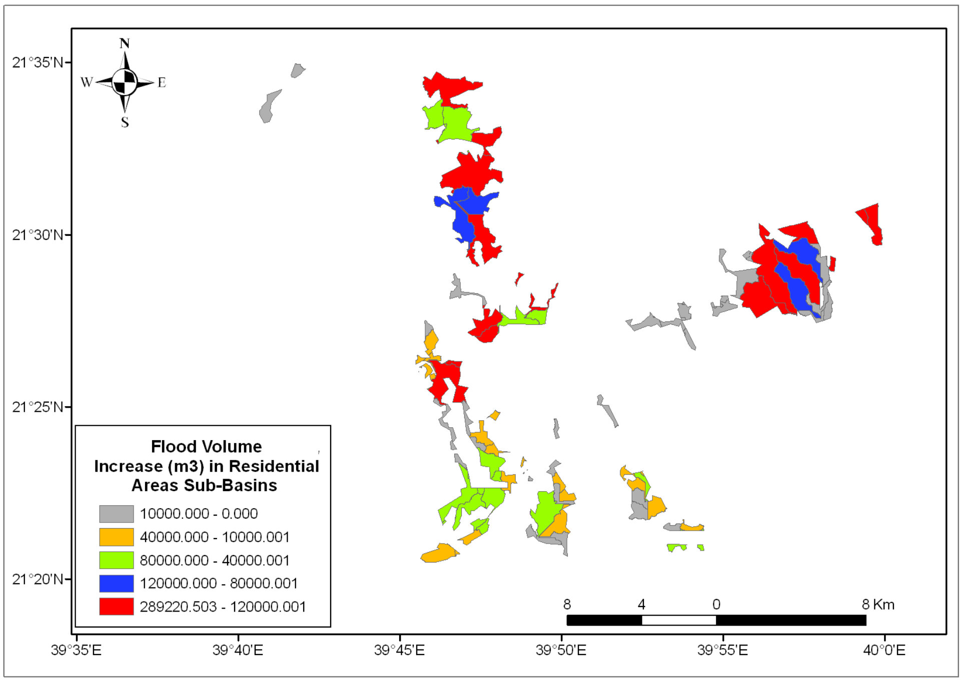
(b) Flood Volume

Fig 11: Floods over Residential Areas in 2010

Comparing the results of flood estimation for both 1990 and 2010 reveals critical points. First, the residential areas of Makkah city have been increased, over twenty years, from 80.0 to 157.6 km2, with 197% increase (with an annual rate of 9.8%). Second, the total flood volumes, of the entire study area, have been increased from 11.8 to 41.3 million cubic meters, i.e. 248%. The spatial distribution of the new residential areas (built between 1990 and 2010) is depicted in figure 12. It can be seen that there are several new areas, particularly in the north of Makkah city, located in high-flood sub-basins. Furthermore, it has been found that most of the new residential areas have been established on sediment soils (Figure 13). From an economical point of view, that geological type is cost-effective than constructing building on solid igneous rock geology. However, that urbanization significantly decreases the permeability of the soil and, thus, leads to a crucial increase in hazardous water surface runoff. For example, the curve number (CN in equation 2) of sediment geology type equals 76 while it equals 98 for paved residential areas (e.g. Sen 2008b, and US NRCS 1986). These two factors might be the major reasons resulted in that sever augmentation of flood volume in Makkah metropolitan area.



(a) Runoff Depth



(b) Flood Volume

Fig 12: Floods over New Residential Areas

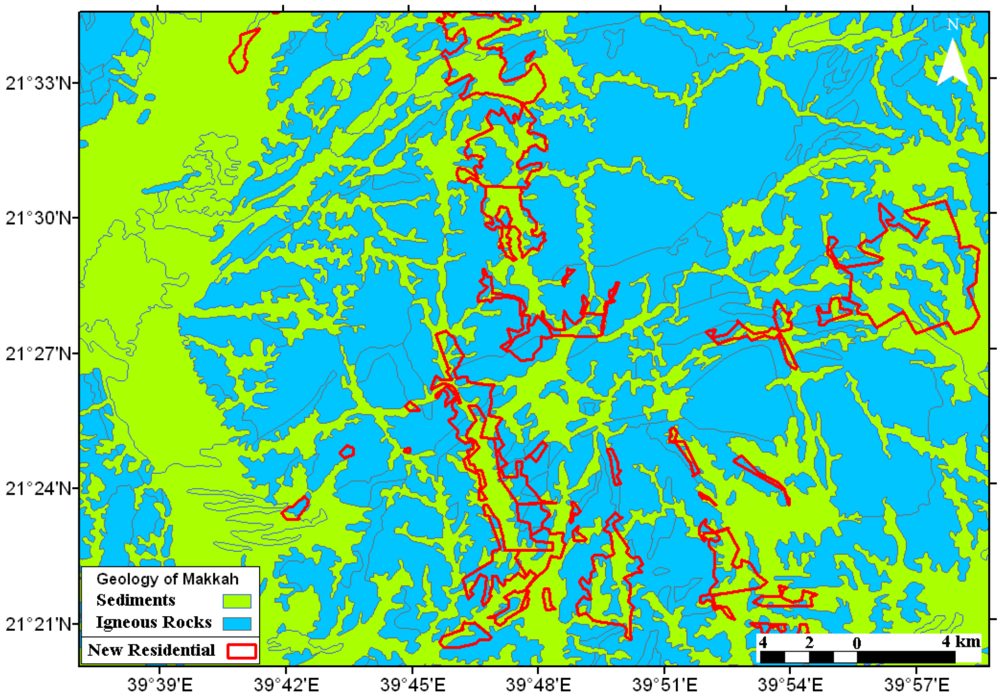


Fig 13: Geology of New Residential Areas

5. CONCLUSIONS

The urban sprawl is one of the human-induced potential threats to sustainable development where urban planning, with effective resource utilization and allocation, is a crucial concern. Thus, identification and analysis of the patterns of sprawl would help in effective land-use planning in an urban area. In the current study, a four-dimensional GIS has been developed to analyze and quantify the urban growth of Makkah city in the last sixty years. Makkah has witnessed a huge urban sprawl in mid 20th century, that might be due the enormous national income expansion due to the oil exploration in the Gulf region. That economical growth commenced an urban development revolution for almost all towns within Saudi Arabia. Also, it has been found that the urban growth in Makkah city takes a radial pattern, which is logically understood knowing that the holly mosque is considered the center of the city, and the central area around it has the highest population intensity since residents and pilgrims prefer to stay close to this mosque. In the context of 4D GIS, it worth mentioning that GIS presents a valuable tool for developing 4D cadastre for land use and real estate of a city (Van Oosterom et al., 2006). Such a project is currently proposed for Makkah city, and can be linked to the GIS-based flood modelling developed in this research.

Applying GIS spatial analysis tools produces more valuable pieces of information. The azimuth of the major axes of the standard deviational ellipse has been found to be 35^{o}, 31^{o}, and 148^{o} for 1947, 1990, and 2010 respectively. Therefore, the urban growth in both 1947 and 1990 took the north-east and south-west directions, while it took the north-west and south-east directions in 2010. Furthermore, inspecting the topography of Makkah city concluded that the urban sprawl mainly exist in low- and moderate-elevation regions. The growth spreads out along the valleys and avoid the mountainous areas for economical reasons. Moreover, it is concluded that the urban sprawl of Makkah city follows regional roads. In the first phase (1947-1990) the urban growth has been concentrated mainly along Makkah-Riyadh and Makkah-Taif roads. However, in the second phase (1990-210) the urban development has been intensive mostly along Makkah- Riyadh and Makkah-Madinah roads. Furthermore, accomplished results showed that the residential regions of Makkah city have been increased by 197%, while the total flood volumes have been enlarged by 248%. Two factors might be considered possible reasons led to that significant flood hazard raising. First, establishment of new residential areas in regions that already posse high flood impacts. Second, building up new suburban areas on sediment soil significantly decreases the permeability of the soil and, thus, leads to a crucial increase in hazardous water surface runoff.

It is concluded that the utilization of GIS in urban growth and flood hazard estimation researches is quit powerful and provides an effective technical tool that helps in analyzing and understanding such phenomena. It is recommended that the attained results should be taken into account by decision-makers in implementing new development planning of Makkah metropolitan area.

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