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A new Approach to Determine the Flood Hazard Impact on Road Network using 3D City Model

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Flood hazard risk, Road network, 3D city model, GIS, flood water depth.

Abstract

Flash flood in urban area strikes mainly the road network. In fact, the streets during flood act as streams or overland flow paths. This jams the traffic, stops the public services, and interrupts the economic activities. Previous studies have treated floods in urban areas as if they were occurring in rural areas. This study presents a new approach that treats the road network as the path of the flash flood water. The new approach uses a 3D city model as the basis for hydrology analysis. This approach regards the building and the streets as part of the terrain that results in water flowing through the streets as it does in reality. The depth of flood water in the streets is calculated and used as a risk factor. Remote Sensing (RS) and Geographical Information System (GIS) technologies are used to obtain and prepare the required input data for the hydraulic model. Various flood scenarios were investigated for different return periods and flood risk code maps for the road network were generated. The obtained results showed that 41.2% of the road network in the study area is under high flood risk from fairly frequent rainfall events, and this percentage reaches 80% to 90% for low frequent flood events (50 years and 100 years flood). The new approach was evaluated by comparing the derived results with actual flood data and had an accuracy of 77%. The results of this study may help decision makers to take the necessary actions to protect people and property.

1. Introduction

Annual flash floods cause loss of human life and damage to property estimated at billions of dollars worldwide [1]. The first vulnerable part in urban area is the road network. Impervious surfaces due to urbanization increase the flood impacts on cities [2], [3]. These impacts include both direct (such as road network cuts and floating vehicles parked along floodplains) and indirect (such as traffic disruption, business interruption, increased carbon

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dioxide emissions) [4]– [7]. Roads during flood are the main cause of human life loss as illustrated by [8]. Many researchers have been attracted to investigate the evaluation of flood impacts on transportation network [9]. Generation of maps that show zones prone to flooding hazards also known as flood hazard maps proved to be the effective way to save both people and property [1]. When these maps are not available, many approaches can be applied to identify locations inundated to flood hazard as summarized by [10]. Those approaches can be divided into two categories, one category for how to estimate flood peak discharge quantities, the other for how to estimate flood risk on road network.

The first category deals with estimation of quantities of flood water according to topographic and morphometric parameters of the study area. Reference [11] categorized the hydrological models in this category according to their complexity into three groups, simple, moderate, and complex. The simple models (e.g., rational method) used for small watershed. It is widely used due to its simplicity and the ability to compromise between theory and data availability [12]. The moderate methods (e.g., curve number (CN)) use more input factors such as land use, geological, and soil properties of the basin to estimate its flood characteristics. The complex models (e.g., The Soil and Water Assessment Tool (SWAT)) which used more data in its processing.

The second category deals with estimation of flood risk on road network. The approaches in this category may also be categorized into three groups according to the parameters used to judge the level of risk. The first group uses only morphometric characteristics of basins in which roads exist as flood risk indicator. With a variation of the number of parameters used from research to another, a total morphometric number from summation of normalized data of each parameter is calculated. The flood hazard for a sub-basin and for its existing road increases as the morphometric number increases [3], [13]– [19]. The second group based on the idea that the higher the runoff volume is in a sub-basin, the more hazard there will be on roads in that sub-basin [20] [21]. The third group considers the runoff water depth in the streams as a flood risk indicator. As the water depth in a stream increases the hazard on roads that intersect this stream increase. The flood water depth according to the studies performed using this approach was computed as the difference between the land surface elevation and an interpolated flood surface. The flood surface boundaries can be generated from the flood extent surveyed points [22], from satellite image during a non-flooded period [23][24] or from flood mapping [25]. The elevation of boundary points was obtained from the Digital Elevation Model (DEM). reference [1] used hydrologic and hydraulic models (WMS, HEC-GeoRAS and HEC-RAS) with manual definition of the channel center lines and banks on both sides of the channels to calculate the flood surface elevation. This approach of using flood water depth as risk indicator is close to realistic but the methods used to calculate the water depth have some drawbacks such as the need for field surveying or satellite image after flood event to determine the flood extent which means that it can’t be used to predict a future flood hazard or the need to use many software and manually input the streams centerlines and banks which make it tedious and time consuming.

3D city models are virtual storage of building location and characteristics. Building data in 3D city models could be in various levels of details (LOD). LOD0 is a representation of footprint polygons while LOD1 is representation of buildings by block model usually obtained by extruding footprints to an average height. LOD2 is a model with roof shape and differentiated heights within a single building. Detailed data about building openings are contained in LOD3 while interior structures of a building are available LOD4 [26]. 3D city models have been used for more than 29 applications in environmental simulations most of them relying on visualization as concluded by [27] beside estimation of building damage from floods [28].

To overcome the drawbacks of flood treatment methods, this paper presents a novel approach to determine the flow network using a 3D city model to mimic the flow of flood water through roads in urban areas. The paper also presents a new simple and efficient computational method for estimating flood water depth in submerged roads. GIS, remote sensing, and metrology data were used as inputs to identify the area most prone to flooding in the different return periods.

2. Methodology

2-1 Study area

Jeddah is the main port on the Red Sea and is an important commercial center. The Jeddah metropolitan area represents for 45% of the catchment area and lies between (21-15'N, 21˚50'N) and (39˚5'E, 39˚20'E) as shown in Figure 1. Jeddah has witnessed a significant increase in the population and, consequently, the transportation infrastructure since 1980 [29]. Residents in Jeddah use private cars for 93% of their transportation [30]. This makes securing the road network against flooding a top priority to save people's lives. Generally, Jeddah has hot weather, but it receives a flood storm from time to time as in November 2009, January 2011, November 2017, and November 2018. These were examples of occasional flash floods with short durations and harmful results as mentioned by [1]. The flood waters start from the Tehama Mountains in the eastern side and carry the surface flow through the city and continue to the Red Sea.

2-2 Data

A feature data set contains different feature classes collected from various sources has been used in flood risk assessment in Jeddah. These layers include ASTER DEM 30 m spatial resolution free of charge available on USGS website, building footprint and street map obtained from Jeddah municipality in CAD format, SPOT satellite multispectral image of 2.5 m resolution from King Abdulaziz City of Sciences and Technology (KACST), soil maps published by Ministry of agriculture and the rainfall data for a period extends from beginning of 1971 to end of 2012 for Jeddah from two rain gauge stations, J134 and JMPE (airport station). The maximum annual daily rainfall for the two stations is shown in Fig. 2.

2-3 Data processing

This study had simulated flood occurrence in Jeddah city due to flash flood. A 3D city model was generated from buildings footprint and used to modify the DEM of Jeddah city. Image analysis and classification techniques were used to generate land use map of the study area. Soil hydrologic groups were generated using soil map. 3D city model, slope map, land use map and soil hydrologic groups were used in Hydrologic Engineering Center-hydrologic modelling system (HEC-GeoHMS) [31] to extract the stream network, catchment area, sub-basins, and hydrologic and morphometric parameters. These parameters and the rainfall data were used with the help of GIS spatial analysis techniques to determine the flood hazard parameters by applying flood formulas. Accordingly, the stream flow paths in the city and the flood water depth on streets were estimated. The results were used to generate road network hazard maps for the different return periods. A flowchart of the proposed approach methodology is shown in figure (3). The stages of data processing are described, in detail, in the following sections.

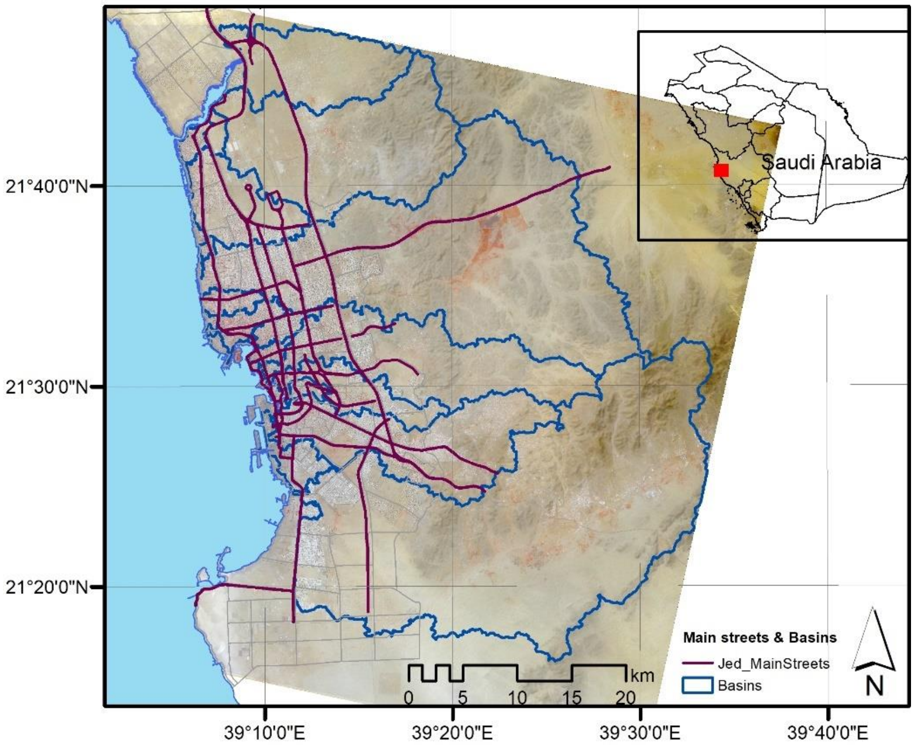

Fig. 1: The study area

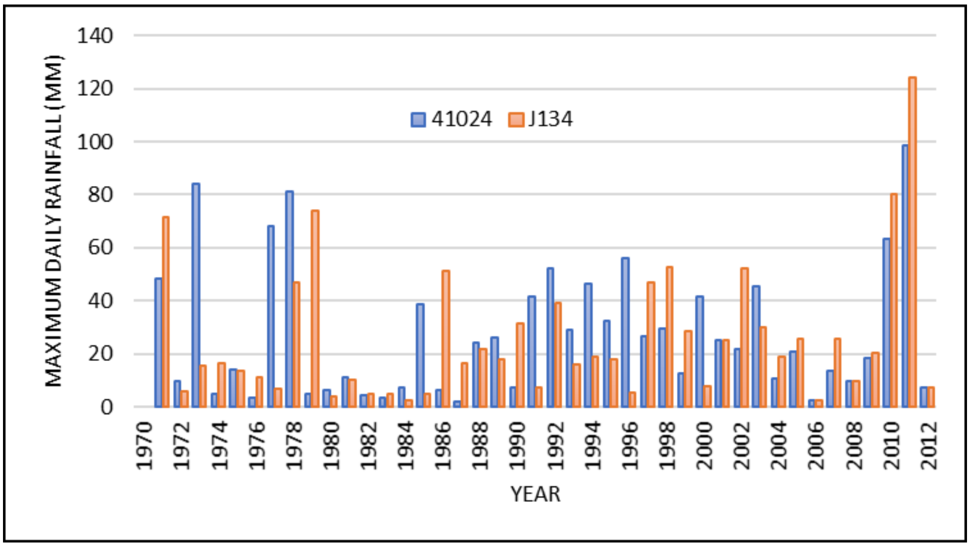

Fig. 2: Rainfall data for the two rain gauges.

2-3-1 3D City Model

In contrast to previous studies, this study simulates the real scenario of flood flow through streets in urban areas. A 3D city model was built to represent the urban area and used in the hydrological analysis model to generate the flood stream network, whose main path would be the streets. The 3D city models can be generated as stated by [32], [33] from 2D urban data, GIS spatial data, laser scanning data, digital photogrammetry, or Open Street Maps (OSM). For this study a LOD1-3D city model was generated from building footprint using GIS. The first step to generate the 3D city model is creating a layer of building footprint polygons, then getting the ground elevation of these polygons from the DEM. The height of each building is then added to the ground elevation to get the roof elevation and convert polygons from vector to raster format. The generated model is lastly used to modify the DEM of the study site to get 3D city model. Figure (4) show graphically the steps of generating LOD1-3D city model from building footprint. The modified DEM was used to generate the stream network that mimic the reality. Figure (5) show a part of 3D city model and stream network in urban area.

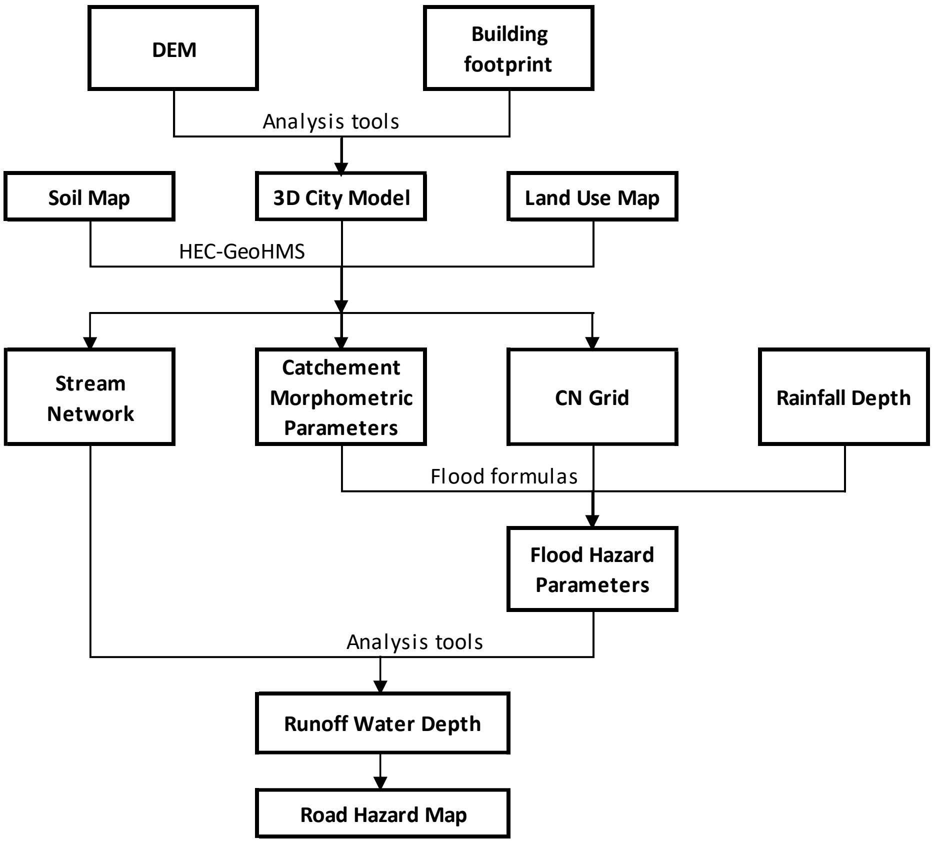

Fig. 3: Proposed methodology flowchart.

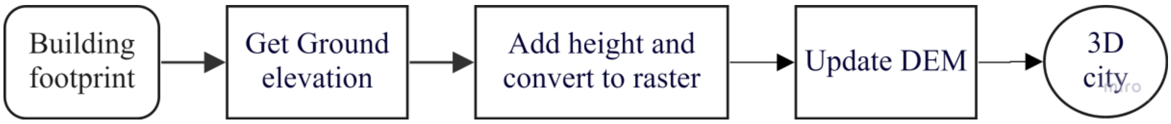

Fig. 4: Process flow of creating 3D City Model.

2-3-2 Hydrology analysis

Hydrology analysis include estimation of rainfall depth at a specific return period, determination of catchment morphometric parameters and estimation of runoff depth and runoff volume. The details of hydrology analysis for the study area can be found in [34]. The main result of that study was producing a risk code map of Jeddah districts as shown in figure (6).

2-3-3 Flood water depth

The volume of runoff water in each sub-basin is not sufficient to be used as a risk factor. The depth of the flood waters is the main risk factor for traffic. To estimate the flood water depth, a series of steps were developed using the spatial analysis tools in ArcGIS as shown in Figure (7). First, the stream network was driven using 3D city model with threshold area of one hectare (a block of 100m x 100m), the sub-basins and their morphometric parameters were also driven. Next, a buffer of distance equal to half the widest street around streams was applied to shorten the affected area in each sub-basin. Then the buffer layer is erased using the building footprint to extract only the area of the affected streets. Back to the sub-basins and calculate the runoff volume for each return period. Join the stream area to the sub-basin layer spatially. The latest step is computing the flood water depth in streets in each sub-basin.

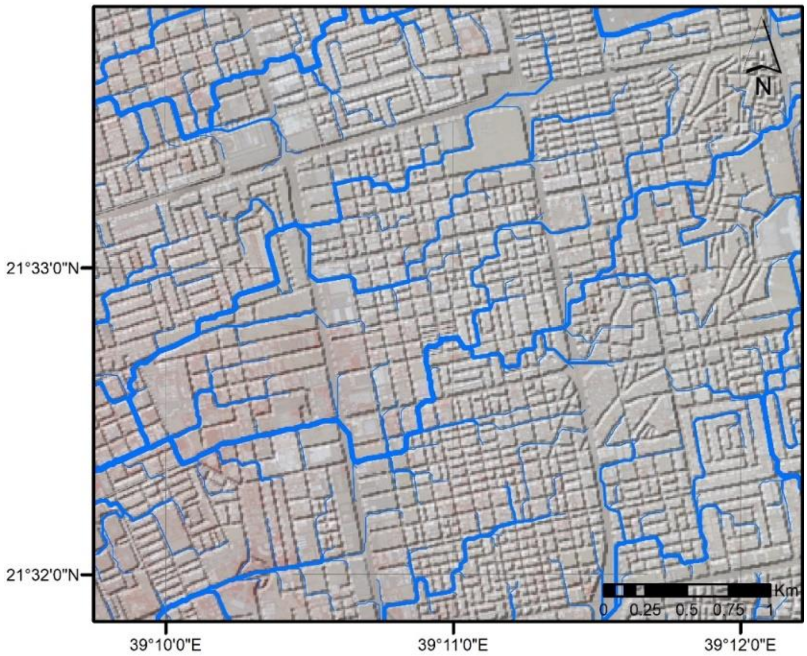

Fig. 5: Stream network in 3D City Model.

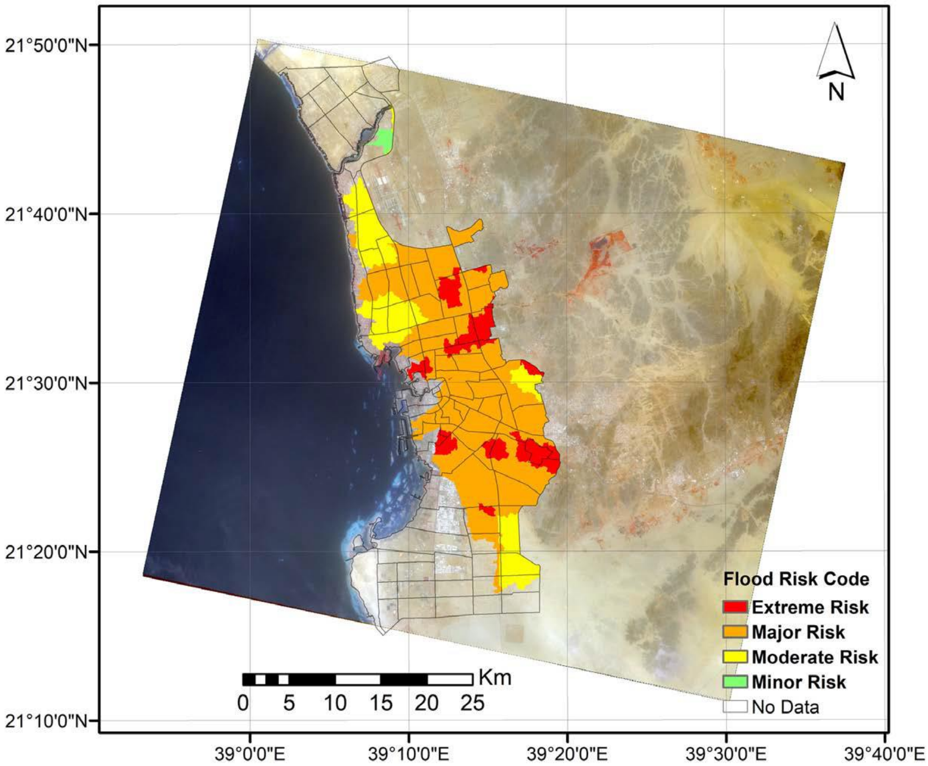

Fig. 6: Districts flood risk code [34]

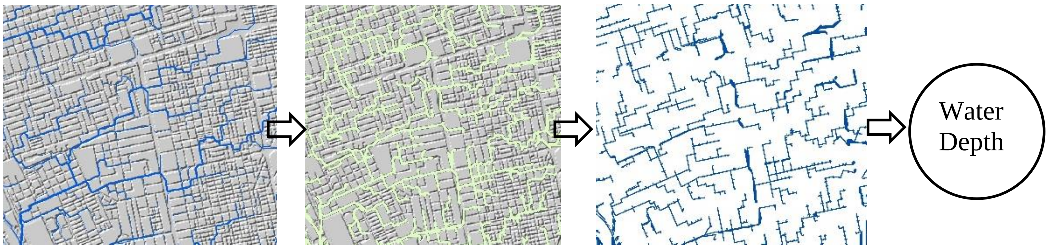

Fig. 7: Process flow of calculating the runoff water depth.

3. Results

The flood water depth that considered a critical threshold for road network has been investigated in many recent researches [9]. Reference [35] used 30 cm as the critical threshold, which indicated the heights of the vehicle's air intakes. Reference [36] recommended a safety limit of 30 cm for passenger cars and 60 cm for emergency vehicles. References [37] and [38] recommended 30 cm as the ultimate threshold at which a passenger vehicles starts to float. Reference [39] sugested close the road if the water depth exceeds 30 cm. Accordinglly, the flood water depth in the study was classified into four classes. Water depth lower than 20 cm was considered a minor risk, between 20 and 30 cm was considered a moderate flood risk, between 30 and 50 cm was considered a maximum flood risk and when the depth exceeds 50 cm was considered an indicator of major flood risk. he proposed approach using a 3D city model to simulate flood flow through the road network was used in combination with the flood water depth calculation methodology to map flood risks on the road network. The flood water depth in each sub-basin is calculated as shown in the process flow in Figure 7. The identity tool is used with the road network layer and sub-basin layer in order to set the corresponding flood water depth for each road. Flood water depths according to the critical depth threshold are grouped into four categories and are used to generate road network flood risk maps. The results of flood depth for different flood return periods are presented in Figure 8. The statistical results of the inundation length of road network for each flood water depth category and different flood return periods are shown in table 1. The percentages of inundated road network for each risk level and flood return period are shown in table 2. Figure 8 show that the southern parts of road network is more vulnerable to flood hazard than the northern parts. The comparison of flood scenarios presented in Figure 8 leads to that the size of the threatened part of road network is directly proportional to the magnitude of preciptation or to the flood return period. With the increase in return period, the parts of road network associated with extreme flood risk increase. Refering to Table 2 it is noticed that the total inundation ratio of road network with water depth higher than 30 cm is dramatically increased from 0.3% for 5 year return period to 41.2% for 10 year return period, indicating that the transportation system and associated fasilities in affected roads are very subject to major flood risk from fairly frequent rainfall events. Due to the absence of sewer system, a 45 mm rainfall event (5 year flooding) will cover 40% of road network with flood water depth > 0.2 m. The accomulation of the water will fill the series of road tunnels and lead to close the roads. This means that Jeddah city needs a very efficient flood drainage system to avoid the disruption of transportation system due to small amount of rainfall preciptation. For low frequent flood events (50 year and 100 year flooding) around 80% to 90% of the road network will be subjected to major to extreme flood risk.

For assessment the accuracy of the proposed approach, a flood risk map was generated using the rainfall data of 2017 flood event with rainfall of 88.04 mm [40] and compared to road condition map published by Jeddah municipality during the event as shown in Figure 9. The lengths of the road network in each risk level are used to produce the accuracy assessment matrix as shown in table 3. The overall accuracy of the proposed approach is 60%. The percentage of underestimated risk levels is 23% while the percentage of overestimated ones is 34%. If the overestimation of the proposed approach is considered as a safety factor, its accuracy will be about 77%.

Table 1: Inundation Length (km) of different water depths for different return period

Water Depth (m)	5-year	10-year	20-year	25-year	50-year	100-year
<0.2	516.745	292.560	124.089	104.697	56.078	21.421
0.2-0.3	350.515	218.950	202.688	179.257	129.134	71.930
0.3-0.5	2.598	355.750	506.880	462.358	296.248	242.024
>0.5	0	2.598	36.201	123.546	388.398	534.483

Table 2: Percentage of road network inundated to flood risk for different return period

Flood Risk	5-year	10-year	20-year	25-year	50-year	100-year
Minor risk (<0.2 m)	59.41	33.63	14.27	12.04	6.45	2.46
Moderate (0.2-0.3 m)	40.30	25.17	23.30	20.61	14.85	8.27
Major Risk (0.3-0.5 m)	0.30	40.90	58.27	53.15	34.06	27.82
Extreme Risk (>0.5)	0.00	0.30	4.16	14.20	44.65	61.44

Table 3: Accuracy assessment matrix of the proposed approach

		Predicted Flood Risk			Grand Total	User's Accuracy
		Minor	Moderate	Major		
Mapped Flood Risk:	Minor	93771	40551	7645	141967	66%
	Moderate	46967	56940	34205	138112	41%
	Major	24680	50929	157459	233068	68%
Grand Total		165418	148420	199309	513147	
Producer's Accuracy		57%	38%	79%		60%

4. Discussion

Our results confirm that the accuracy of the proposed approach for determining the impact of flood risks on the road network is over 75%. Using a 3D city model allows the authors to identify the threatened roads in each sub-basin. The suggested method of calculating the flood water depth is easy and straight forward. The volume of runoff water and the area of the affected roads can be easily computed and accordingly the flood water depth can be easily calculated. Comparing our method to that suggested by [22] which need field surveying after flood event to determine the flood extent and flood surface elevation and use them to calculate the flood water depth one can figure out how easy our method is. Also the method of [22] can’t be used to predict a future flood hazard as it depends on field measurements after the flood event while ours can as shown in the context. Our suggested approach of using 3D city model automatically generate the flood streams in the urban area which is time and effort saving comparing to the method of [1] which needs many software and manually input the streams centerlines and banks which make it tedious and time consuming.

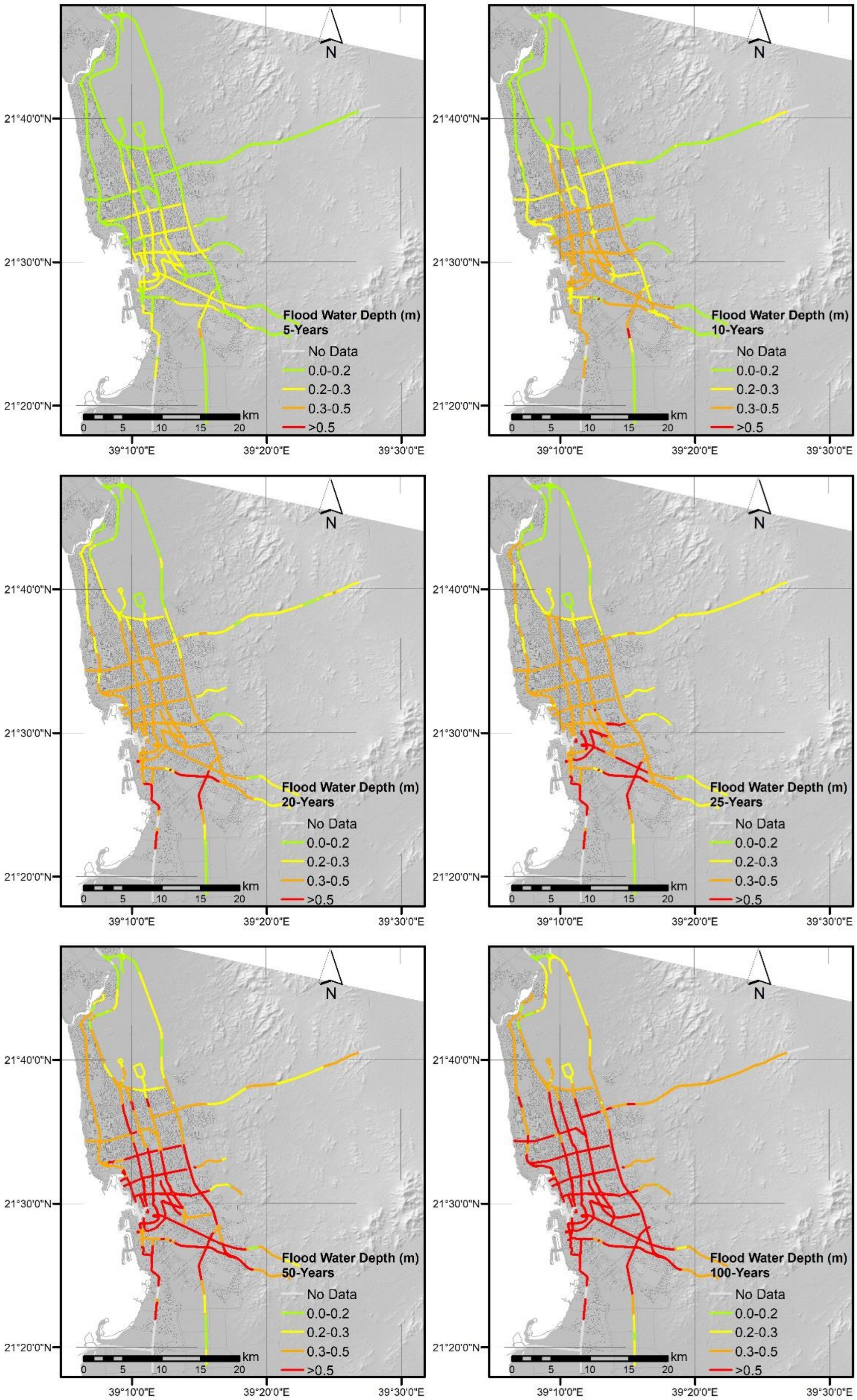

Fig. 8: Flood water depth for different return periods.

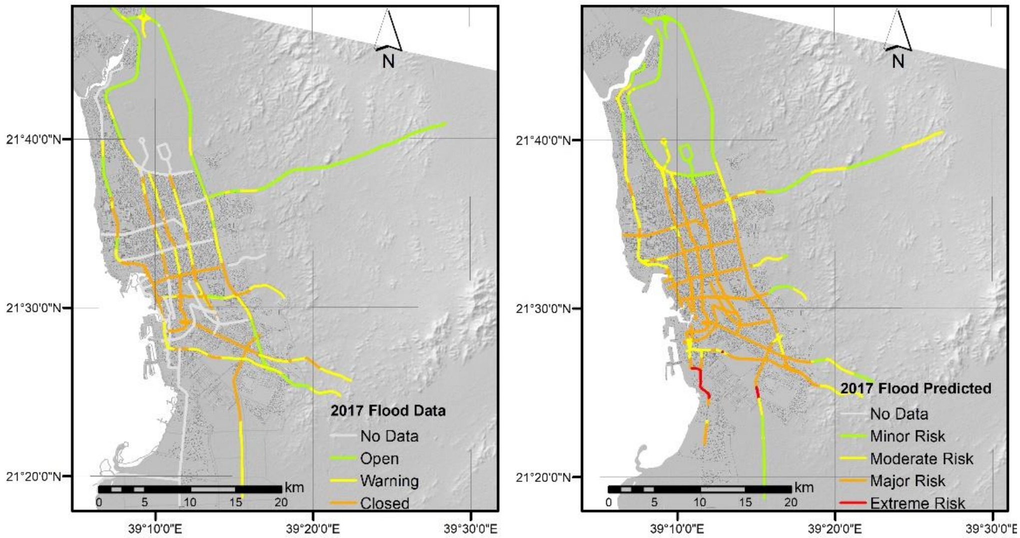

Fig. 9: Road network status during 2017 flood (real (left) and predicted (right)).

5. Conclusions

This research presents a new approach to predict the effect and map the risk of flash flood on road networks. The proposed approach integrates the use of 3D City model and an easy method to estimate the flood water depth. The 3D City model simulate the flood streaming through urban road network and flood water depth used as a risk factor of the flood event. The methodology proposed in this paper could be adopted for applications in road network facing flood hazard. The new approach has been assessed through the comparison of the derived results to the actual flood data and its accuracy reached to 77%. The results obtained show that 41.2% of road network is subjected to major flood risk from fairly frequent rainfall events (5 year and 10 year flooding). For low frequent flood events (50 year and 100 year flooding) around 80% to 90% of the road network will be subjected to major to extreme flood risk. The results of this study also show the need to effecinet flood drainage system to avoid closing roads even for a small amount of rainfall preciptation.

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نهج جديد لتحديد تأثير مخاطر الفيضانات على شبكة الطرق باستخدام نموذج المدينة ثلاثي الأبعاد

الملخص العربي

تضرب السيول المفاجئة في المناطق الحضرية شبكة الطرق بشكل رئيسي، تعمل الطرق أثناء ذلك كمسارات للسيول مما يؤدي إلى ازدحام حركة المرور وإيقاف الخدمات العامة وتعطيل الأنشطة الاقتصادية. عالجت الدراسات السابقة السيول في المناطق الحضرية كما لو كانت تحدث في المناطق المفتوحة. تقدم هذه الدراسة طريقة جديدة تتعامل مع شبكة الطرق كمسارات لمياه السيول كما يحدث في الواقع. تستخدم الطريقة الجديدة نموذج ثلاثي الأبعاد للمدن كأساس للتحليل الهيدرولوجي حيث تكون المباني والشوارع جزءًا من التضاريس التي تؤدي إلى تدفق المياه عبر الشوارع كما هو الحال في الواقع. يتم حساب عمق مياه السيول في الشوارع واستخدامه كمعامل خطورة. تُستخدم تقنيات الاستشعار عن بعد (RS) ونظام المعلومات الجغرافية (GIS) للحصول على بيانات الإدخال المطلوبة وإعدادها للنموذج الهيدروليكي. تم دراسة سيناريوهات السيول لفترات التكرار المختلفة وتم إنشاء خرائط تبين درجات الخطورة على شبكة الطرق. أظهرت نتائج البحث أن ٤١,٢٪ من شبكة الطرق في منطقة الدراسة معرضة لخطر السيول بشكل كبير من أحداث الأمطار المتكررة كل ٥ الى ١٠ سنوات، وتصل هذه النسبة إلى ٨٠٪ إلى ٩٠٪ للسيول التي تتكرر كل ٥٠ و١٠٠ سنة. تم تقييم الطريقة الجديدة من خلال مقارنة النتائج ببيانات السيول الفعلية وكانت بدقة ٧٧٪. قد تساعد نتائج هذه الدراسة متخذي القرار في اتخاذ الإجراءات اللازمة لحماية الأشخاص والممتلكات.