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Urban Surface Characteristics Study Using Time-Area Function Model: A Case Study in Saudi Arabia

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Abstract

The study of surface characteristics in urban catchments is critical step for stormwater planning, design and management. At present, nearly all GIS-based distributed parameter models for rainfall runoff calculation neglect the urban environment properties in Digital Elevation Models (DEMs), thus simulation results by these models were hardly reliable especially in urban areas. In this study, a physical-based hydrologic model using time-area function method was developed for unit hydrograph derivation taking surface characteristics of urban environment into consideration. With the growing availability of high-resolution DEMs produced by airborne LiDAR, the basic approach was to calculate the runoff travel time from each cell of DEMs in the watershed to the outlet by determining the flow path and accumulating the travel time through each cell along the path. This standalone model, named Time-Area Function (TAF) model, was then applied to a city in Saudi Arabia and was compared with a conventional model. It showed that for the case study TAF model could give more reliable and reasonable results. In conclusion, rainfall runoff analysis in urban environment requires additional properties to be considered and modelled, and significant improvements can be achieved by approaches as implemented and applied in TAF model integrating urbanization components, such as buildings, varying landuse, open channels and drainage system into the model.

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Keywords: Stormwater; Urban environment; GIS; DEMs; Time-Area Function method

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1. Introduction

In urban and suburban areas, paving and other impermeable surfaces combined with limited, ageing or poorly maintained drainage obstruct rain and snow melt from soaking into the ground. This significantly increases the volume and velocity of stormwater runoff. With increasing urbanization in watersheds, impervious coverage increases, thereby reducing infiltration. Reduced infiltration increases the possibility and intensity of flooding[1]. Furthermore, extreme rainfall events associated with climate change amplify the effect on existing flood risk. This type of flooding is also becoming more dangerous and more costly to manage because of the higher concentrations of population and their assets in the urban environment. Thus, urban flooding is a serious and growing development challenge[2]. However, conventional approaches to study hydrologic process hardly take urban environment prosperities into consideration. In addition, a high degree of input data are normally required by sophisticated and detailed physically based models. Some of the instances of these models have been developed in the past such as MIKE URBAN and PCSWMM[3]. In contrast, this work presents a new Time-Area Function (TAF) model integrated with urbanization components such as buildings, landuse change, channel and drainage system. Meanwhile, this model is able to compute the travel time within catchment and then generate the synthetic unit hydrograph accordingly. All this, in turn, gives better representation of urban catchment and will enable the planners to cope with urban flooding easily.

This study presented here is a part of flood modeling and mitigation of a city in Saudi Arabia project which the Stormwater Experts - *Geschäftsführer der Ingenieurgesellschaft Prof. Dr. Sieker mbH* is in charge of. The main purpose of developing this model is to be used for surface characteristics studying instead of the existing NASIM-ArcView-Extension Time Integral Function model (abbreviated as NASIM model), which is developed by *Hydrotec Ingenieurgesellschaft für Wasser und Umwelt mbH*. In addition, the TAF model itself is a standalone application which runs in a Windows Operating System computer.

2. Time-Area Function Model Concept

The TAF model is a GIS-based model integrated with urban environment properties which quantifies the travel time of rainfall to the basin outlet. The basic idea is to use the GIS raster data to calculate the travel time from each cell in the watershed to the outlet by determining the flow path and accumulating the travel time through each cell along the path. The model accounts for difference of velocities over land, through pipes in drainage system and on buildings, and in open channel. The parameter required for calculating different velocity includes slope grid deriving from DEM data, rainfall excess intensity, and surface roughness resulting from different land use. Flow path is following the flow direction gird by applying D8 (8 direction) approach[4] flow model to DEM data.

The key of this model is to combine two different urban runoff computation concepts: Model A) Time-Area Method and Model B) Non-linear Reservoir (kinematic wave) Method. Model A provides a hydrograph with a user-specified time of concentration and might be suitable for larger urban catchments as well as rural catchments. On the other hand, Model B generally results in the hydrograph peak occurring just when heavy rainfall ceases. Model B is therefore best suited to small urban catchments[5]. The invention of this novel method owns to the higher resolution of mapping products especially DEMs. Therefore, this model is suitable for both rural and urban catchment.

2.1. Runoff flow velocity

The main flows and routing method modelled in the TAF model are illustrated in Fig. 1 constituting three main flows:

(1) Overland flow: The runoff velocity for areas with overland flow may be estimated using a kinematic wave approximation. The depth of flow at equilibrium is given by Overton and Meadows[6]:

$$y = \left(\frac{i_e n x}{\sqrt{S_o}} \right)^{0.6} \tag{1}$$

where y = depth of runoff flow at equilibrium (m)

i_e = rainfall excess intensity (m/s)

n = Manning's roughness coefficient ($s/m^{1/3}$)
x = distance along the flow plane (m)
S = slope (m/m)

The equilibrium depth of flow from equation is again used in Manning's equation to calculate the equilibrium runoff velocity.

$$v_o = \frac{1}{n} y^{2/3} S^{0.3} = \frac{(i_e x)^{0.4} S^{0.3}}{n^{0.6}} = K_s^{0.6} (i_e x)^{0.4} S^{0.3} \tag{2}$$

where: v_o = overland flow velocity (m/s)

K_s = Strickler roughness coefficient ($m^{1/3}/s$), reciprocal of Manning's n value

(2) Open channel flow: The open channels in urban areas are described based on following simplifications and assumptions: 1) The geometry of channels is regular and treated uniformly along the channel since urban area channels are mostly constructed by people with similar shape and size within a specific area. 2) The location of channels is given instead of recognizing it by accumulation grid, which could be more realistic and practical in urban area. Therefore, under these hypothesis, the open channel flow velocity is calculated simply using Manning's equation[7]:

$$v_c = \frac{1}{n} R^{2/3} S^{1/2} = K_s R^{2/3} S^{1/2} \tag{3}$$

where: v_c = mean flow velocity in the channel (m/s)
R = Hydraulic Radius (m)
S = slope (m/m)

Hydraulic Radius is the ratio of channel cross sectional area and wetted perimeter, shown below:

$$R = \frac{A}{P} \tag{4}$$

where: A = channel cross sectional area (m^2)
P = wetted perimeter (m)

(3) Horizontal pipe flow: A drainage system in urban area is a network of pipes used to convey stormwater and/or wastewater. In this system, only stormwater is taken into consideration. From design point of view, free surface flow exists for the design discharge; in addition, the pipes are of commercially available circular sizes. Therefore, following assumptions are used in this study about pipe flow: 1) Pumping stations and pressurized pipes are not considered here. 2) All pipes are of circular sizes, with known roughness, length, diameter, slope and inlets. 3) Steady and uniform flow condition are assumed.

The pipe flow velocity is given by well-known Colebrook-White formula[8]:

$$v_p = -2\sqrt{2gSD} \log\left(\frac{k_s}{3.7D} + ?\frac{2.51\nu}{D\sqrt{2gSD}} \right) \tag{5}$$

where k_s = internal pipe roughness (m)

S = hydraulic gradient or friction slope, hf/L (m/m)
ν = kinematic viscosity of water (m^2/s)
D = internal pipe diameter (m)
g = acceleration of gravity, 9.81 m/s^2

The pipe flow velocity is previously calculated in a vector data using the equation above, and the model will directly read velocity from the vector data.

(4) Vertical pipe flow: In urban areas, the existence of buildings including residential and commercial houses, governmental offices, schools, and other constructions interrupt flow paths, prolonging flow length of the rain path on building roofs. Three simplifications are made: 1) Buildings roofs flows into a vertical pipes and reaches ground, and there is no additional storage in the building to harvest rainfall, and when the slope of cells exceeds a certain threshold, the cells appear to gather water. 2) This vertical pipe flow velocity is additional input parameter, which is decided by modeller. 3) The prolonged flow length equals the height of the building, and its height is approximated by multiplying the slope of the cell and its size. To sum up, when the slope of a grid cell S exceeds a critical value S_c:

$$S_c = \frac{3}{cellsize} * 100 \tag{6}$$

where 3 = the height of one floor (m)

S_c = the critical slope (%)

The extra time cost in this cell equals:

$$t_b = \frac{h_b}{v_b} \tag{7}$$

$$h_b = \frac{S * cellsize}{100} \tag{8}$$

where t_b = travel time in vertical pipe (s)

h_b = the height of the building (m)

v_b = flow velocity in vertical pipe (m/s)

2.2. Travel time

Once the flow direction and the parameters needed for flow velocity calculation are prepared, it is time for travel time calculating. If a flow path from cell j to the outlet traverses m cells, $m = 1, 2, \ldots, M_j$, the flow length L_j is defined as the sum of the flow distances through each cell along the path[9] :

$$L_j = \sum_{m=1}^{M_j} l_m \tag{9}$$

where l_m = flow distance (m)

If the velocity in cell m is v_m, the cumulative travel time T_j from the cell j to the outlet can be similarly computed by summing the travel time through each cell along the flow path as:

$$T_j = \begin{cases} \sum_{m=1}^{M_j} \frac{l_m}{v_m} & S < S_c \\ \sum_{m=1}^{M_j} \left(\frac{l_m}{v_m} + t_b\right) & S \geq S_c \end{cases} \tag{10}$$

where t_b = travel time in vertical pipes at cell m

S_c = critical slope (m/m)

To avoid the zero denominator when computing travel time in Equation (10), *Given minor slope at flat area* is introduced as a parameter for the flat area after depression filling of DEM as flow velocity v_m is a function of slope in all flow velocity formulas, i.e. Equations (2), (3) and (5).

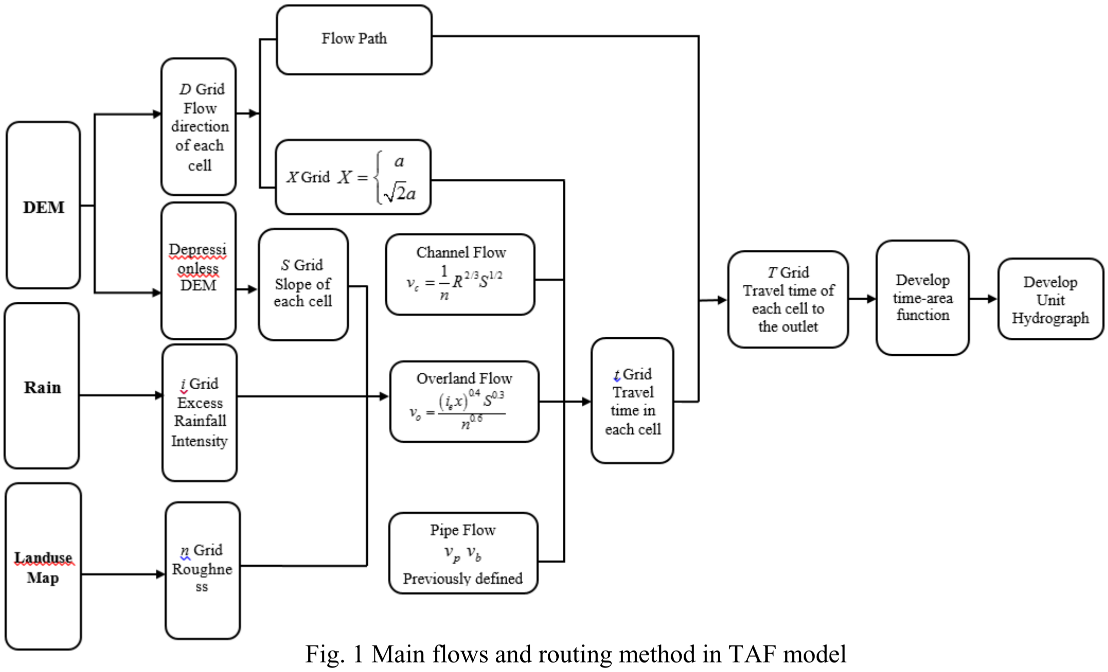

Fig. 1 Main flows and routing method in TAF model

3. Case Study

3.1. Problem description

The application of the TAF mode is demonstrated here on the problem of studying surface characteristic for the flood modeling and mitigation of a city in Saudi Arabia. The city is situated in the Eastern province in the Kingdom of Saudi Arabia. It has suffered severe floods, and is facing more challenges in the future due to climate change, population growth and urbanization. To address the problem, the hydrological model - STORM developed by *Geschäftsführer der Ingenieurgesellschaft Prof. Dr. Sieker mbH* was used in this project. For pre-study and the input requirement of STORM, time-area curve of the study area are necessary. Instead of using conventional and commercial NASIM model, a new and open source software is required, and it is going to be integrated with STORM in the future.

3.2. Methodology

The schematic diagram of the case study given in Fig. 2 explained in detail as follows:

- Delineate the study catchment: The catchment delineation by ArcGIS is based on the DEM data from the airborne LIDAR survey, produced and processed by Mapping Solutions ltd, UK in 2015.
- Build QGIS based C++ programming environment with Qt Designer for interface design: QGIS, previously known as Quantum GIS, is a powerful and open source geographic information system. Qt Designer is Qt's tool for designing and building graphical user interfaces (GUIs) from Qt components, which is also an open source tool. C++ is used as programing language in order to be integrated with STORM in the future.
- Develop TAF model: The concept of this model is illustrated in Fig. 1.
- Verify the model by comparing with NASIM model and carrying out sensitivity analysis: Five test cases (A, B, C, D and E) were selected to verify the model, and three critical parameters were chosen to do sensitivity analysis. Five test cases were sub-catchments of the study area while three critical parameters were *Roughness*, *Rainfall Excess Intensity* and *Given minor slope at flat area* respectively.

- Apply the model to the study area: After model verification, it is ready to be apply to the study area. Two outputs are expected, including cumulative time-area curve of the urban catchment and unit hydrograph derived from time-area histogram.

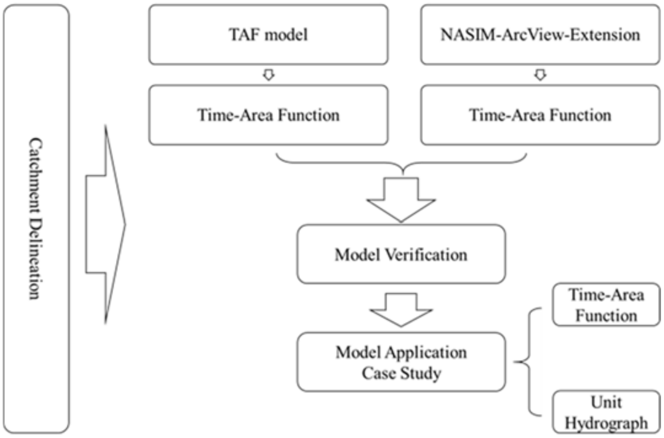

Fig. 2 Main flows and routing method in TAF model

3.3. Model evaluation

Four criteria were selected to evaluate the performance of this model:

- **Ease of model use:** McPherson[10] states that there is evidence of simulation failures that have been attributed to model inadequacies where the blame more properly belonged to improper handling by the user because of the insufficient comprehension of the complex processes involved. Thus, the simulation techniques adopted should not exceed the level of mastery of such tools by the user. Therefore, the ease of application use is not only associated with the complexity model itself, but also depends on the experience and knowledge of individual users.
- **Computational time:** Considering larger geographic areas with finer resolution in GIS database today, computational time is crucial factor to evaluate a GIS-based hydrologic model. For a moderately large catchment, it takes NASIM model hours to run. Hence, it is important to make sure it does not take too long for one simulation.
- **Sensitivity of output to changes in parameters:** As pointed out in the sensitivity analysis section, whether the parameter and its associated system component should be excluded or included depends on the sensitivity of output to changes in parameters. The parameter in a model should be proved to be sensitive to the system, otherwise the parameter may be redundant and can be excluded from the model.
- **Theoretical limitations of the model:** A hydrologic model is used to describe and simulate status and process of the hydrologic cycle. The complexity of the hydrologic process makes a completely described model impossible. Therefore, simplification and assumption are essential to develop a successful model, and theoretical limitations thus exists. Regardless of how developed a theory is, it has limitations. All types of models have their own particular area of effectiveness in rainfall-runoff modeling, depending on the objective of a study and the desired accuracy[11].

4. Result and discussion

TAF model for the project was developed and verified by comparison with NASIM model and sensitivity analysis. It turns out that the model was sensitive to all the three variables. Small alterations of the parameter produce large changes in the objective function, and this gives an idea of how accurate that parameter must be to create a reliable model that can be used for predictions[6]. In terms of comparison between two models, without available measured runoff at the watershed outlet, it was hard to give objective judgments about which model has more accurate results. However, NASIM model gave realistic representation of depressions in DEMs while TAF model presented better travel time maps[12]. Furthermore, no drainage system was included in the TAF model nor the NASIM model. Regarding roughness of land surface, varying values were both available in two models. However, Rainfall Excess Intensity is another crucial parameter that was missing in NASIM model, especially when it came to designing for rainfall events with different return periods, seen in Table 1. The detail of model development and verification can be found in master thesis by Jiang[12].

Table 1. Setup of NASIM and TAF model.

Inputs & Parameters		NASIM model	TAF model
Inputs	Case A	DEM, .tif format; boundary, .shp format	DEM, .tif format
	Case B	DEM, .tif format; boundary, .shp format	DEM, .tif format
	Case C	DEM, .tif format; boundary, .shp format	DEM, .tif format
	Case D	DEM, .tif format; boundary, .shp format	DEM, .tif format
	Case E	DEM, .tif format; boundary, .shp format	DEM, .tif format
Parameters	Roughness ($m^{1/3}/s$)	10	10
	Rainfall Excess Intensity (mm/hr)	NA	15
	Given minor slope at flat area (%)	NA	1.00E-07& 1.00E-05

Fig. 3 shows the two main output of TAF model, while Fig. 4 presents synthetic unit hydrographs with and without varying land use. It was re-potted in Excel deriving from the time-area histogram computed by the model. First of all, the travel time map directly represented the varying land use in reality. Second, as can be seen in Fig. 4, the model gave reasonable unit hydrographs with characteristics of urban catchment. There were several bumps in the time-area curves before runoff resulting in an equilibrium discharge due to impacts of urbanization. Areas like roads, concrete playground, plazas contributed to faster drainage of runoff, affecting runoff concentration. That was possibly the reason that although the hydrograph was attenuated at the large area of residential area the peak flow rate was still increased. To sum up, time-area curves and unit hydrographs under varying land use were computed. The time-area histogram, however, did result in the S-hydrograph shape, which made the result conclusive.

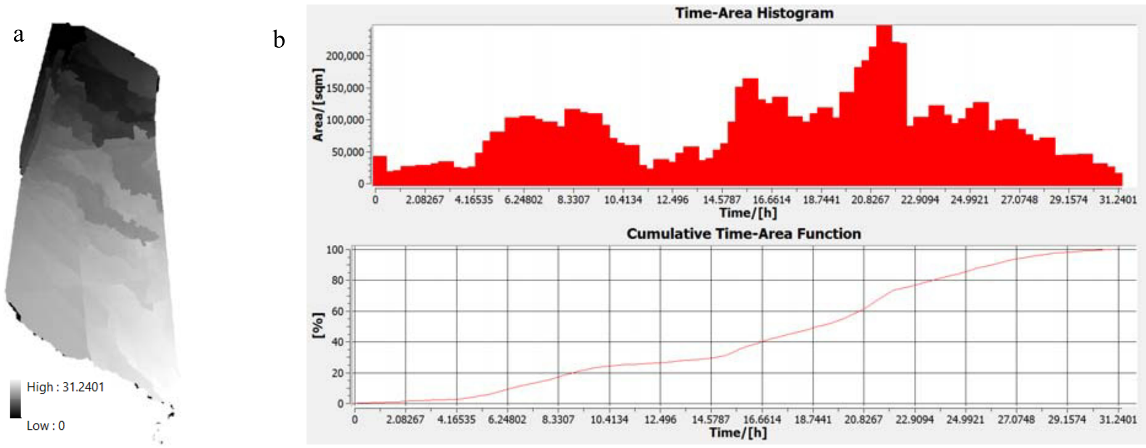

Fig. 3 (a) Travel time map; (b) Time-Area Histogram with Cumulative Time-Area Function

In this case study, drainage network and open channel were not provided but an imaginary created drainage and channel network was tested. Its capability of dealing with a complex drainage system and open channels was verified[12]. For further validation, however, test on cases with drainage system and channel networks provided are necessary.

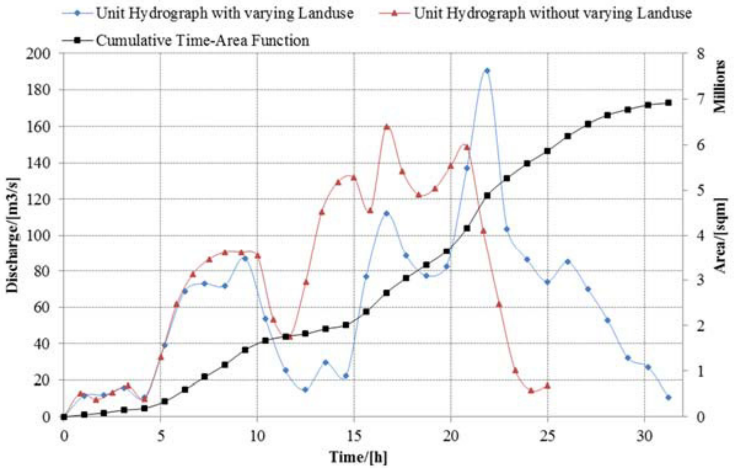

Fig. 4 Synthetic Unit Hydrographs and Cumulative Time-Area Function

5. Conclusion

The city in Eastern province of Saudi Arabia is facing a problem of severe flooding, so the surface characteristics of downtown area were studied in this paper. To address this issue, the TAF model was first developed and successfully applied to the study case. The model took spatially varying land use into account and gave better representation of urban surface characteristics by providing travel time map and time-area curve. One of its advantages is that it can be freely used since it is based on open source QGIS. Compared with NASIM model, TAF model requires more variables or parameters and cost less computational time. However, depression and its storage effects cannot be simulated in TAF model. In addition, as the model can hardly be applied to flat area, it is better to use 2D model. To achieve more reliable results, the current TAF model still needs to be further improved, tested and evaluated for other urban and rural catchments. This study demonstrated that significant improvements can be achieved by approaches as implemented and applied in TAF model integrating urbanization components, such as buildings, varying landuse, open channels and urban drainage system into the model.

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