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Full Length Research Paper

Quantification of urbanization impacts on discharge volume using H2U model

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Urbanization tends to change in peak discharge and runoff volumes of natural catchments. In this study, the results of H2U model with the production function used for net rainfall calculation were compared to observed hydrographs. In the production function, mapped impervious area (MIA) and effective impervious area (EIA) values were tested for imperviousness parameter. A test catchment located in Tehran City was selected for this purpose whereas; part of this area was considered to compare pre and post developed conditions. Performance indicators verified that urban catchment hydrographs most closely resembled the observed hydrographs when using effective impervious area value in the production function. The comparison of pre and post development hydrographs in part of the catchment revealed urbanization leads to 95% increase in peak discharge rate and 50% decrease in unit hydrograph time base. The post developed condition runoff volume of 10 year return period rainfall event was 4.01 times more than pre developed runoff volume originated from decreasing hydraulic length and increasing impervious areas. Moreover; the results of this study revealed that the effect of Strahler order drainage network change on peak discharge rate was greater than decrease of hydraulic length.

Key words: Effective impervious area, morphological approach, net rainfall, urbanization.

INTRODUCTION

Urbanization tends to change in peak discharge and runoff volumes in natural catchments it replaces. Impacts of urbanization in flood magnitudes (Espey et al., 1966; White and Greer, 2006) and flood duration (Seaburn, 1969) have been investigated in some studies. Although, recognizing complex nature of rainfall -runoff transformation processes of urbanized area and determining hydrologic response of urban catchment depends on recorded rainfall –runoff data or other data describe environment of study area; most urban catchments are ungauged and have no runoff data. As a result the models predict urban hydrograph without rainfall runoff data is preferable. Rainfall runoff modeling includes two processes, production function and transfer function. Production function determines the net rainfall received to the outlet and the transfer function spreads the net rainfall over time and space in the river basin (Fleurant et al., 2006). Geomorphological approaches (Rodriguez-Iturbe and Valdes, 1979; Valdes et al., 1979; Rodriguez-Iturbe and Gonzalez-Sanabria, 1982) takes in to account transfer function by realizing relationships between catchment response and the geomorphological parameters such as the main stream length, bifurcation ratio and length ratio while using IUH (instantaneous unit hydrograph) theory.

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Also, contributing area flow distance function extracted directly from a digital elevation model (DEM) without the assumption of Strahler stream ordering may be used to derive a geomorphologic instantaneous unit hydrograph (Snell and Sivaplan, 1994). The regression relationship of this approach with limited determinism was improved while considering the self-similarity of the drainage network for proposing analytical model such as the H2U model with the global properties (Duchesne et al., 1997). H2U (from French "Hydrogramme unitaire universel") is a simple transfer function, for predicting natural and urban catchments hydrographs (Duchesne et al., 1997; Rodriguez et al., 2005), investigating irrigated terraces influence on the basins hydrological response (Gatot Sumarjo et al. 2001) and modeling floods in hillside catchments (Nasri et al., 2004). The production function of rainfall runoff modeling may be determined based on mapped impervious area ,MIA, (Chen and Adams, 2007), whereas; the effective impervious area, EIA, defined as the portion of mapped impervious area, MIA, (Sutherland, 1995) was one of the most important parameters of the production function. The EIA values may be determined by various methods such as fine-scale multispectral satellite imagery interpretation (Suk Han and Burian, 2009) or field measurement method (Forootan et al., 2011). Due to changes in water management policy and land use, using the morphological models such as H2U is a necessity for predicting urban runoff in semiarid regions with the lack of rainfall-runoff information, Moreover; comparing MIA and EIA values for net rainfall calculation specify the runoff portions do not direct to drainage system.

The objectives of the present study are: (i) to consider MIA and EIA values in the production function for net rainfall calculation; (ii) to investigate drainage network length and order effect on peak discharge rate and compare pre and post development condition of the study area.

MATERIALS AND METHODS

Discharge simulation

In order to apply H2U model in the rainfall-runoff simulation, the following convolution integral should be calculated:

$$Q(t) = S\int_0^t R_{net}(\tau)U(t-\tau)d\tau \qquad (1)$$

$$Q(t) = Flow(m^3/s)$$

S = Catchment's area (m^2)

R_{net} = Net rainfall (m)

$U(t-\tau)$ = Transfer function as the unit hydrograph (H2U)

And τ is the time convolution variable.

Transfer function (H2U model)

In this study, the transfer function was calculated by the H2U model, which is a gamma law type based on the Strahler order (1952), mean hydraulic length $\overline{L}$ and hydraulic length L of the water paths through the drainage system as following (Duchesne et al., 1997; Cudennec et al., 2004):

$$\rho(L) = \left(\frac{n}{2\overline{L}}\right)\frac{1}{\Gamma\left(\frac{n}{2}\right)}L^{\frac{n}{2}-1}\exp\left(-\frac{nL}{2\overline{L}}\right) \qquad (2)$$

where Γ is the Gamma function; and n denotes Strahler order of the catchment.

Hydraulic length is the distance followed by water from the beginning of a first-order stream to the outlet of the catchment.

By introducing M as the mean velocity, the behavior of the drainage network was characterized by the following function (Duchesne et al. 1997; Rodriguez et al., 2005):

$$U(t) = \left(\frac{n}{2\bar{t}}\right)^{n/2}\frac{1}{\Gamma(\frac{n}{2})}t^{(n/2)-1}\exp\left(-\frac{nt}{2\bar{t}}\right) \text{ if } t \le t_{max} \text{ and } U(t)=0 \text{ otherwise} \qquad (3)$$

Where $\bar{t} = \overline{L}/M$ is the average travel time through the network to the outlet, t_{max} is the time of concentration, $U(t)$ denotes the IUH ordinates, and t is sampling time interval.

Production function

In this study, total net rainfall was a summation of the area-weighted net rainfall from the impervious and pervious areas of the catchment calculated, separately (Chen and Adams, 2007).

$$R_{net} = \begin{cases} 0 & v \le s_{di} \\ hv_{im} & s_{di} \prec v \le L_{per} \\ hv_{im} + (1-h)v_{pe} & v \succ L_{per} \end{cases} \qquad (4)$$

Where v is rainfall volume, L_{per} denotes pervious area losses such as depression storage value (ASCE, 1992), infiltration volume and initial loss listed in Table1 and v_{pe} is pervious area runoff calculated by subtracting L_{per} from v value, whereas; impervious area runoff (v_{im}) is obtained after subtracting the depression storage volume s_{di} (ASCE, 1992) from rainfall volume. Moreover; the fraction of mapped impervious area (MIA) and effective impervious area (EIA) values were considered as h parameter, respectively. In this study, MIA were extracted from comprehensive studies of the test catchment (District No.22 of Tehran City Municipality, 2002) and EIA value which is the percentage of effective impervious area such as streets with gutters directly connected to the drainage system was estimated by direct measurement (Forootan et al., 2011).

A Geo-referenced vector image of the test catchment drainage network in the post development condition and the Strahler order

Table 1. Physical characteristics of the test catchment.

Value	Parameter
1.25	Impervious area depression storage (mm)
2.5	Pervious area depression storage (mm)
0.013	Initial soil wetting infiltration loss in the pervious area (mm)
7.2	Ultimate infiltration capacity (mm/h)

method and topological analysis of the links between vectors were extracted from previous study (Forootan et al., 2011) whereas; net rainfall of 14 rainfall events were calculated by considering EIA and MIA values. For determining the importance of drainage network length, it was assumed upper part of the test catchment was drained to the stream located near the study area and down part was drained to the outlet, then unit hydrograph of down part sub catchment was compared to unit hydrograph of the whole test catchment with the same Strahler order, Moreover; for investigating drainage network order effect on peak discharge value, Strahler order of selected sub catchment with the same condition of hydraulic length was changed and unit hydrograph was obtained.

Also, urbanization effect on peak discharge and runoff volume of the selected sub catchment was specified by employing topography map of pre development condition. Obtaining flow direction, flow accumulation by means of Arc-GIS soft ware leads to identify pre development drainage network of the selected sub catchment whereas; performing Strahler order method for pre and post developed drainage system of the selected sub catchment and estimating the water path from each sampling point to the outlet of pre and post development condition result in the provision of H2U model unit hydrographs for both conditions, moreover; pre and post development condition were compared for 10 year return period rainfall volume obtained from the nearest rain gauge station of the study area (Mehrabad rainfall station).

Data collection

Rainfall gauges do not exist in the study area, thus the observed rainfall events was measured by one tipping-bucket rain gauge based on the assumption that rainfall over the catchment is homogenous whereas; the velocity of each runoff event (V) was recorded at the outlet by micro-propeller current meter and the area of cross section (A) was estimated by measuring water level during 10 min time steps from 9/17/2009 to 3/24/2010 for discharge calculation ($Q = A.V$).

STUDY AREA

The test catchment is located in the upper part of District number 22 of Tehran, between 35° $45'$ N and 35° $46'15''$ N and 51° $15'15''$ E and 51° $16'10''$ E, in a semiarid region of Iran (Figure 1). The catchment, which has an area of 67.8 ha, is composed of different land uses such as residential and commercial areas, road way, and green area. The fraction of mapped impervious area was estimated to be 76% (District number 22 of Tehran City Municipality, 2002). By assuming upper part of the test catchment was drained to the stream located near the study area, one sub catchment (21.7 ha) which has the most land use change (87% impervious area) in down part of the catchment is selected (Figure 2) for comparing pre and post development condition.

RESULTS

In this study; net rainfall of each event was estimated by employing two values of 76% (mapped impervious area) and 46%(effective impervious area), respectively and their hydrographs of H2U were compared to observed hydrographs by means of performance indicators such as coefficient of residual mass (CRM); root mean square error (RMSE) and relative difference of peak discharge rates (PEQ) (Bhadra et al., 2008). Two events of the 14 observed rainfall-runoff were selected at random and the effects of impervious area value on the test catchment hydrographs were shown in Figure 3.

The RMSE, CRM values of H2U simulated discharges (Table 2), were the closest to zero when effective impervious area was used in the production function. Also, the maximum absolute relative difference of peak discharge, PEQ, with effective impervious area were the lowest values which revealed closely resemblance of observed and simulated hydrographs. As can be seen in Figure 3, the application of mapped impervious area for net rainfall calculation of H2U model leads to over-prediction of the discharge volume which performance indicators verified these over- estimations. The average of the difference between predicted runoff volumes of MIA and observed values is 30.57% which revealed that approximately 30% of runoff volumes in this region do not drain to drainage system directly. Field measurement showed that 27.85% of this portion direct to wells and the rest (2.15%) drain to grassed area.

Also, as can be seen in Figure 4 changes in maximum hydraulic length of the test catchment from 1975 to 1296 m leads to increase in peak flows from 0.085 to 0.096 and decrease in the unit hydrograph length from 50 to 28 min.

However, the assumption of n=3, n=5 without any changes in hydraulic length of the selected sub catchment resulted in peak rates of 0.063 and 0.105, respectively. Moreover; comparing pre and post development unit hydrograph of the selected sub catchment revealed that urbanization leads to 95% increase in peak discharge rate and 50% decrease in time base of unit hydrograph (Figure 5). Moreover; the runoff volume and peak discharge rate of post developed condition for 10 year return period rainfall event (42.9 mm) was 4.01 and 4.28 times more than pre developed runoff volume and peak value (Figure 6) originated from decreasing hydraulic length, and increasing impervious areas. The reduction of maximum and average hydraulic length and increase of stream order drainage system after development can be seen in Table 3.

DISCUSSION

In this study, accurate H2U hydrographs were obtained using the effective impervious area in the production function, whereas; some studies (Duchesne et al., 1997;

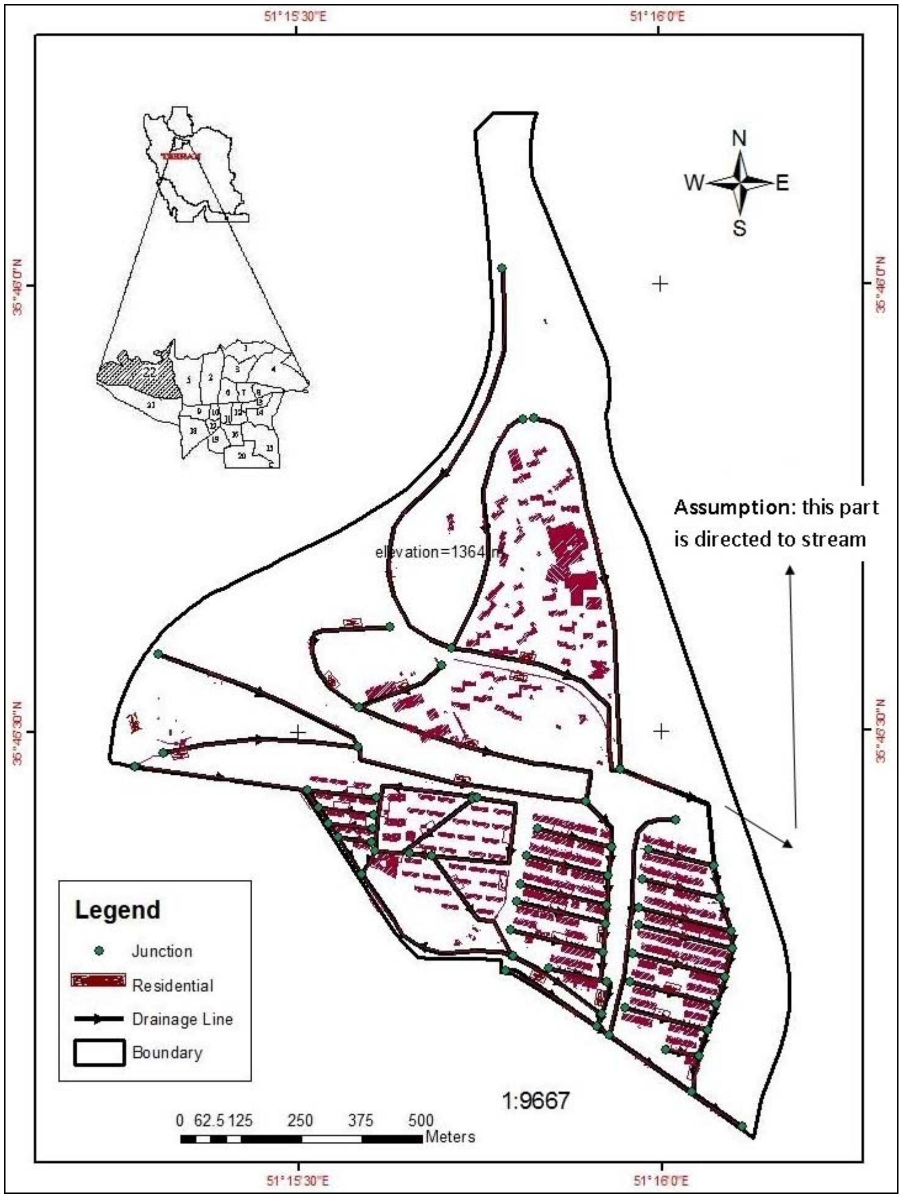

Figure 1. Drainage network of study area.

Chen and Adams, 2007) indicated satisfactory results by employing total impervious area value and assuming the total impervious area is connected to the drainage system of urban catchments. Moreover; comparing observed hydrographs with the H2U hydrographs of MIA values specify 30.57% of runoff volume do not drain to drainage system directly. In the test catchment, some rooftops drain runoff in to the wells, grassed areas and they are not connected to drainage system directly.

To omit this part, only effective impervious area value should be employed for runoff simulations. In the post development condition, 34.37% same Strahler order causes 11.45 to 44% decrease in the peak flows and the unit hydrograph length, respectively, whereas; increase in Strahler order from 4 to 5 without any hydraulic length changes causes 23.52% increase in peak values and decrease in Strahler order from 4 to 3 resulted in 25.88% reduction in unit hydrograph peak discharge rate of the selected sub catchment located down part of the study area. Although; changes in length or final order of drainage network affect peak discharge value, the effect of Strahler order drainage network change on peak discharge rate is greater than decrease of hydraulic length.

As a result; paying attention to appropriately design of drainage network resulted in peak rate attenuation. Both of Strahler order and hydraulic length were changed in the post developed condition of the selected sub catchment which comparing pre and post developed unit hydrograph indicated that the length of pre- developed

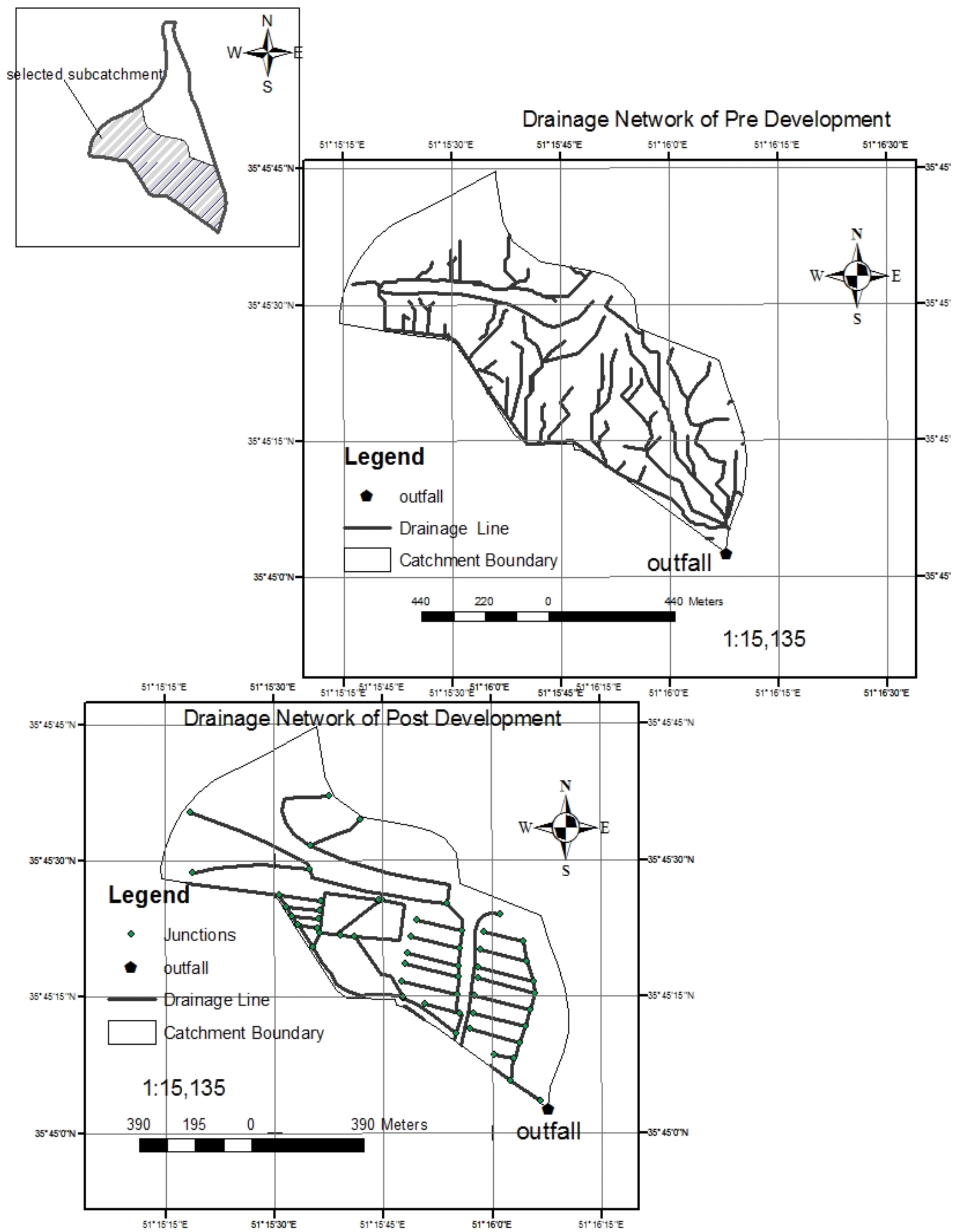

Figure 2. Pre and Post development drainage network in part of study area.

unit hydrograph was twice more than post developed unit hydrograph, moreover; the tail of post developed unit hydrograph was shorter than pre developed unit hydrograph. Urbanization leads to increase of 87% in the impervious area value and decrease of 38.69 to 44.55% in maximum and average hydraulic length of the sub catchment, respectively. Rose and Peters (2001) revealed that peak flows of urbanized catchments were 30% to more than 100% greater than less urbanized and non-urbanized catchments whereas; the peak discharge value of post developed unit hydrograph of this study was 95% greater than pre developed condition unit hydrograph.

The findings of this study revealed the other studies results (Espey et al., 1966; Rose and Peters, 2001; Seaburn, 1969) compared the urbanized and non urbanized areas flood volume and duration. In this study H2U model which includes few paramenter was employed for

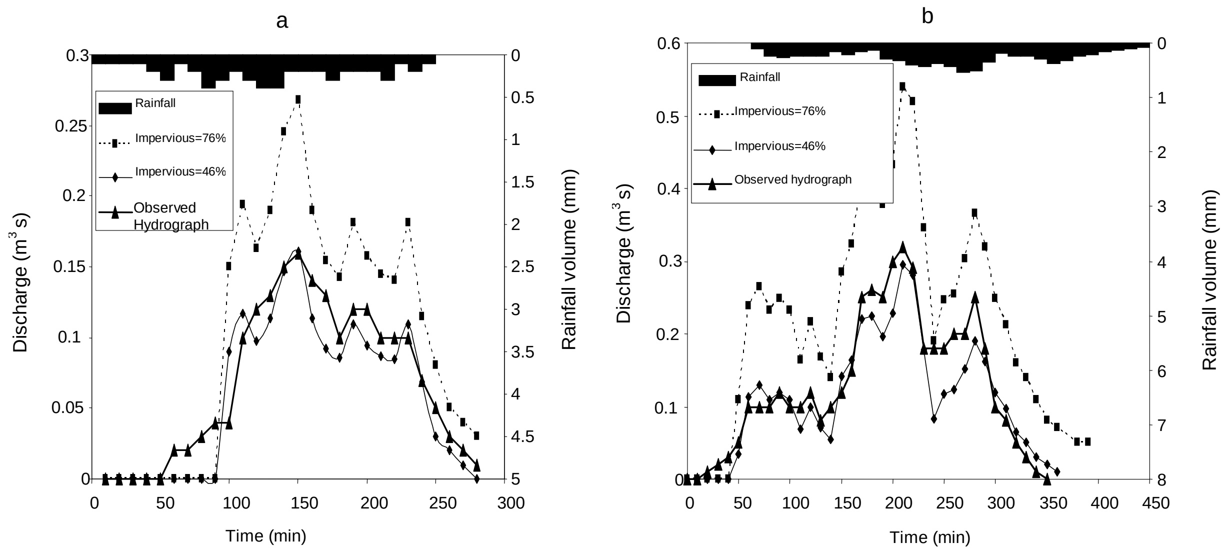

Figure 3. H_2U with MIA and EIA imperviousness values. (a) H2U with Different imperviousness for 5.4 mm rainfall volume (b) H2U with Different imperviousness for 10.5 mm rainfall volume.

Table 2. Performance indicators for simulated discharge evaluation.

No.	Date	Rainfall volume	Runoff percentage do not drain to drainage system	H2U with different impervious values	
				EIA=46%	MIA=76%
1	9/17/2009	3	28.07	PEQ=0.06 RMSE=0.009 CRM=0.063	PEQ=-0.56 RMSE=0.045 CRM=-0.67
2	9/19/2009	5.4	32.49	PEQ=0 RMSE=0.025 CRM=0.12	PEQ=-0.68 RMSE=0.061CRM=-0.52
3	########	6.6	37.8	PEQ=-0.07 RMSE=0.02 CRM=0.02	PEQ=-0.89 RMSE=0.063 CRM=-0.78
4	########	1.5	23.71	PEQ=-0.09 RMSE=0.006 CRM=0.11	PEQ=-0.87 RMSE=0.06 CRM=-0.38
5	11/1/2009	3.5	21.6	PEQ=-0.08 RMSE=0.06 CRM=0.04	PEQ=-0.36 RMSE=0.23 CRM=-0.41
6	11/4/2009	14.4	48.34	PEQ=-0.1 RMSE=0.04 CRM=0.06	PEQ=-1.06 RMSE=0.16 CRM=-0.97
7	########	2.8	31.11	PEQ=0.19 RMSE=0.006 CRM=0.05	PEQ=-0.44 RMSE=0.05 CRM=-0.49
8	12/9/2009	2.3	20.8	PEQ=0.09 RMSE=0.03 CRM=0.29	PEQ=-0.66 RMSE=0.06 CRM=-0.23
9	########	6	39.14	PEQ=-0.14 RMSE=0.12 CRM=-0.17	PEQ=-1.0 RMSE=0.39 CRM=-0.98
10	########	8.8	35.77	PEQ=-0.05 RMSE=0.03 CRM=0.1	PEQ=-0.75 RMSE=0.09 CRM=-0.85
11	2/3/2010	10.5	41.7	PEQ=0.07 RMSE=0.03 CRM=0.03	PEQ=-0.76 RMSE=0.12 CRM=-0.55
12	2/4/2010	6.4	19.69	PEQ=-0.2 RMSE=0.08 CRM=0.05	PEQ=-1.14 RMSE=0.17 CRM=-0.35
13	2/19/2010	5.6	25.11	PEQ=0.06 RMSE=0.03 CRM=0.10	PEQ=-0.31 RMSE=0.05 CRM=-0.38
14	3/24/2010	5.8	22.76	PEQ=-0.13 RMSE=0. 11 CRM=0.19	PEQ=-0.53 RMSE=0.32CRM=-0.47

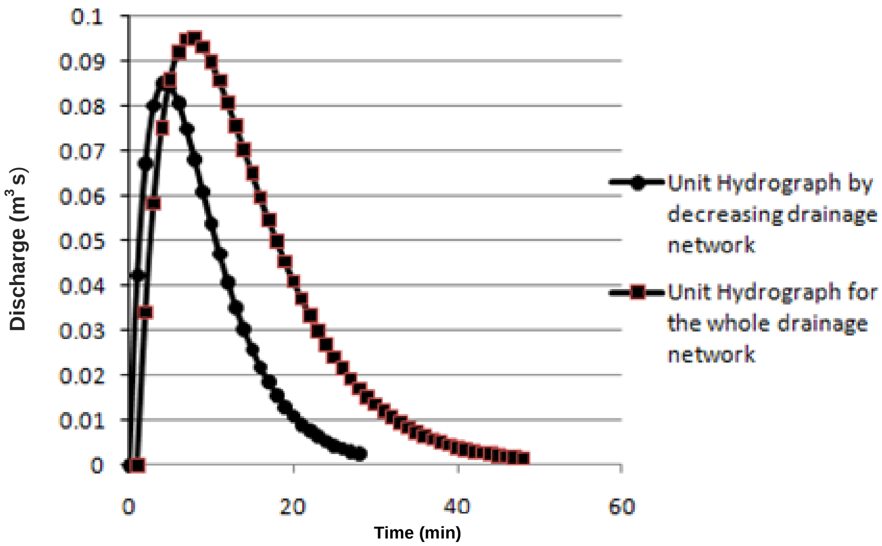

Figure 4. Decreasing hydraulic length effect on unit hydrograph.

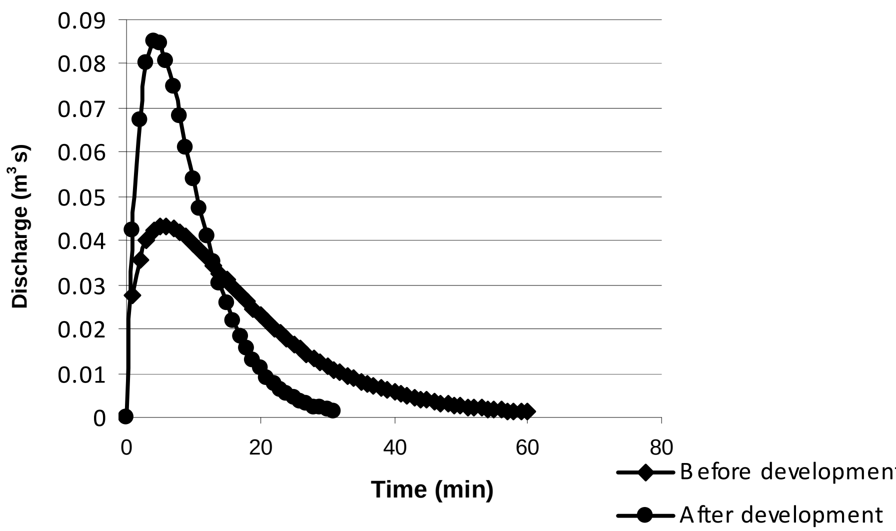

Figure 5. Unit hydrograph of pre and post development in part of the study area.

quantifying runoff volume of urban catchment. This model is based on the assumption of homogeneity of the mean velocity within the area and it is suitable to predict hydrograph in semiarid regions with the lack of information whereas; it can be employed for specifying the effect of land use and drainage network change in discharge volume.

Conclusion

Urbanization changes in land use and drainage network of the catchment. Estimating the impacts of development is necessary for appropriate design of storm water control facilities. The H2U is a simple model which quantifies the influence of drainage system and impervious area value in peak discharge volume and flood duration. Using this model for investigating hydraulic length and drainage network order effect on peak discharge value helps to design drainage network of urbanized catchment appropriately. Comparing observed and predicted hydrographs of two impervious values revealed that employing effective impervious area result in better predicted runoff compared to total impervious area value. Moreover; calculating net rainfall by MIA and EIA determine the runoff volume do not direct to drainage system directly which managing this part of runoff is survival in semiarid regions with the lack of precipitation.

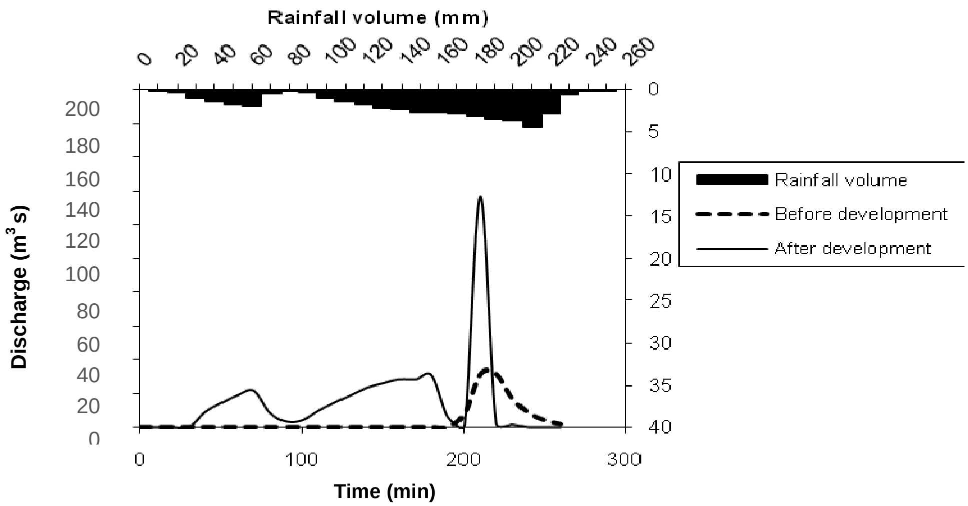

Figure 6. Pre and post development hydrograph of 42.9 mm rainfall event.

Table 3. H_2U model parameters for pre and post development conditions.

condition	n	L_{max} (m)	$\overline{L}$ (m)
Pre-development	3	2114	1147.03
Post -development	4	1296	635.93

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