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Runoff Curves Development for Al-Adhaim Catchment Using Digital Simulation Models

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ABSTRACT

A rainfall-runoff model is used to develop runoff curves through simulating runoff processes. The runoff curves are developed by inserting various equations related to runoff calculations and runoff coefficients. The runoff model used in this study is the Stanford Watershed Model after it has been properly modified.

Application of the various parameters and their effects on runoff rates are investigated. Based on the results of this application, the monthly simulated runoff rate indicated significant level of sensitivity to various model parameters.

The Modified Stanford Watershed Model is operated and applied on Al-Adhaim catchment. The relationship between runoff coefficients and rainfall concentration times is explained for different variables and parameters. Runoff curves accordingly provide a better and more accurate estimate for runoff coefficients.

KEYWORDS: Runoff curves, Al-Adhaim catchment, Digital simulation models, Modified Stanford Watershed Model.

INTRODUCTION

Surface water hydrology deals with the movement of water along the earth's surface as a result of precipitation and snow melt. Detailed analysis of surface water flow is highly important to such fields as municipal and industrial water supply, flood control, stream flow forecasting, reservoir design, navigation, irrigation, drainage, water quality control, water- based recreation and wildlife management (Visseman, 1996).

Runoff occurs when precipitation moves across the land surface, some of which eventually reaches natural or artificial streams and lakes. Runoff often transports contaminants to these water bodies, reducing their usefulness as a source of water (National Association of RC and D Councils, 2001).

The relation between rainfall and runoff is influenced by various storm and basin characteristics. Because of these complexities and the frequent paucity of adequate runoff data, many approximate formulae have been developed to relate rainfall and runoff. The earliest of these formulae were usually empirical statements. The trend now is to develop descriptive equations based on physical processes, and so there are several types of models according to the purposes for which they are designed (Visseman, 1996).

In this study, the relationship between the runoff coefficients and concentration times during different return periods will be developed and runoff curves accordingly concluded. Runoff coefficients will be then used to calculate the runoff volumes.

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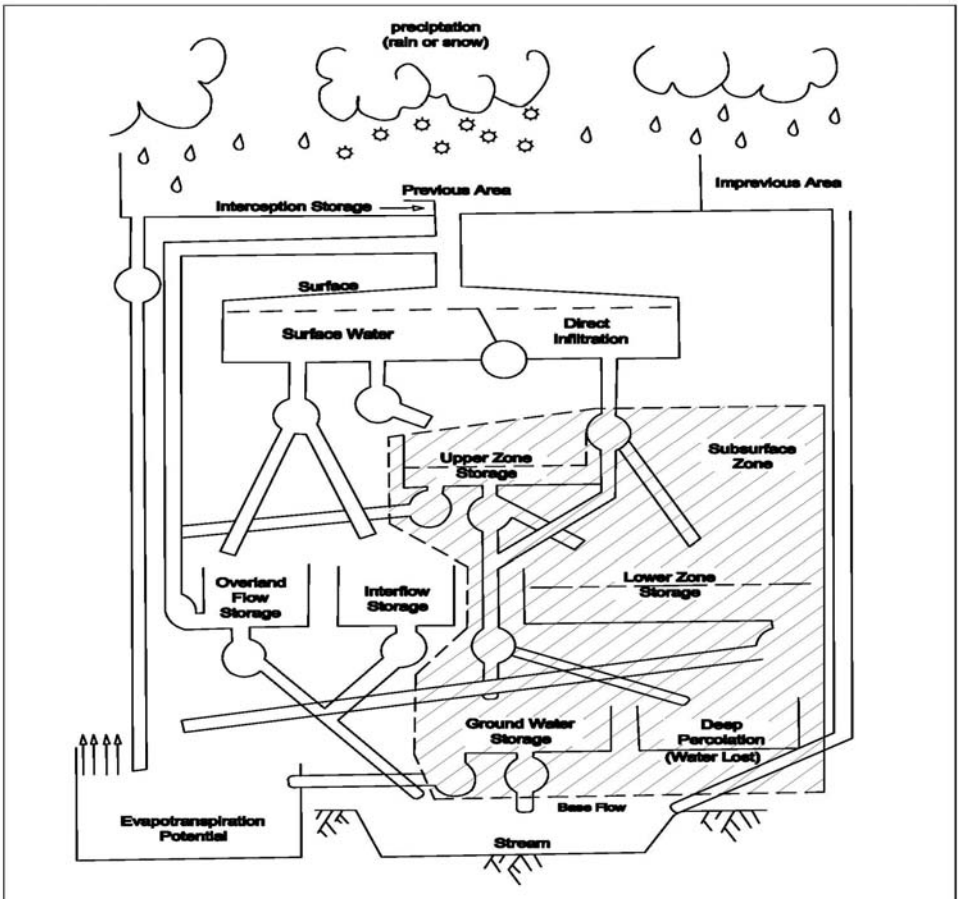

Figure 1: Schematic of Stanford Watershed Model (Ali, 1998)

OBJECTIVES

The aim of this study is to satisfy the following objectives:

1- Development of runoff curves inserting the functions of the Stanford Watershed Model (SWM).
2- Calculate runoff coefficients using formulae dependent on the various physical characteristics of the coefficients.
3- Establish the relationship between runoff coefficients and concentration times by using the runoff curves.

LITERATURE REVIEW

Sikka and Selvi (2005) used experimental examination of rational runoff coefficient for small agricultural and forest watersheds in the Nilgiris. The rational method is widely used for estimating peak flows for small rural watersheds and urban drainage design throughout the world. Estimation of time of concentration (t_c) using empirical formulae and runoff coefficient (C) from available tables is the major source of uncertainty in the application of rational method. Three commonly used times of concentration t_c methods were compared and the values of C are presented for different methods of t_c. The probabilistic rational method was also demonstrated to determine values of runoff coefficient C for different recurrence intervals. In small agricultural and forest watersheds of Nilgiris, it was found that the relative error in using the commonly used Kirpich formula under predicted time of concentration as compared to observed t_c was in the range of 74% to 89%. As a result, standard tabulated values of runoff coefficient C when used with Kirpich t_c significantly over-estimate peak discharge using rational formulae for small agricultural watersheds, forest watersheds and watersheds with grasslands.

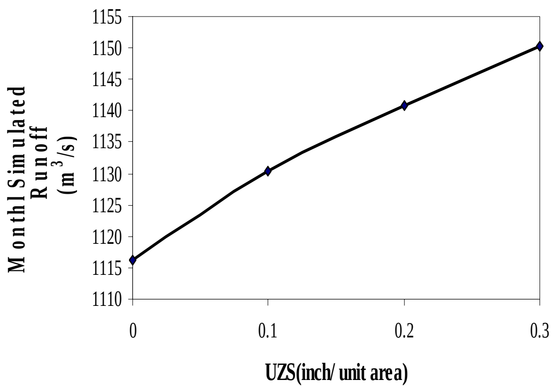

Figure 2: The effect of the parameter (UZS) on monthly simulated runoff

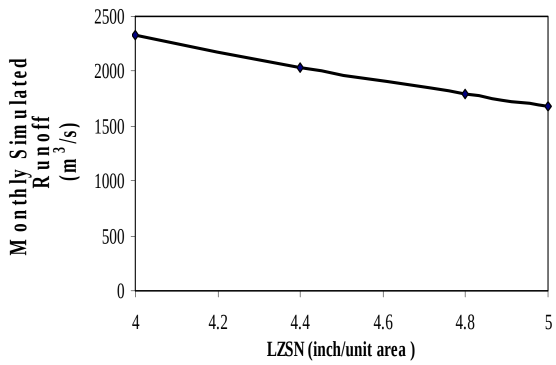

Figure 3: The effect of the parameter (LZSN) on monthly simulated runoff

Kemp-Benedict and Huber-Lee (2006) used daily rainfall data and Intensity-Frequency-Duration (IDF) curves to estimate the impact of land cover change on rainfall runoff. Total rainfall was not sufficient for understanding the catchment dynamics and reservoir filling and discharge. Instead, the rainfall pattern for an entire storm, or at least the peak intensity, is needed. While this information is not directly available, typical patterns are represented by Intensity-Duration-Frequency (IDF) curves. A standard parameterization of IDF curves can be used to obtain a probability density of peak intensity, given the total rainfall from a storm. The main result of this study was the formula for the conditional probability of peak storm intensity, given a total amount of rainfall that exceeds the infiltration capacity of the soil under different land covers in the Buriti Vermelho catchment within the San Francisco river basin .

Feng and Li (2008) studied scale effects on runoff coefficients. Six meso-scale and large-scale sub- basins of the Luanhe river basin, in the northeast of China, were selected for calculating the runoff coefficients of single events during 1956-2002. An obvious reduction in average runoff coefficients from o.43 (Liuhe basin) to 0.1 (Luanhe basin) was found with increasing the basin area. For the annual runoff coefficients from 1956 to 2002, the same trend was also observed. In addition, runoff coefficients varied wildly from one rainstorm to the other. One of the reasons is that at the beginning of the storm, the rainfall is absorbed in the soil and fills in the macro-pores of the soil, and after runoff generation rainfall infiltrates during the routing process. The spatial variability of rainfall and the groundwater discharge ability can also lead to runoff coefficient reduction with increasing the basin area. This study on the scale effects on runoff coefficients is very important to develop a physically-based hydrological model and parameter estimation on different scales.

MODEL STRUCTURE

The Stanford Watershed Model (SWM) is used to develop the runoff curves.This model is developed by inserting the equations relevant to runoff coefficient calculations. A schematic of an overall picture of the SWM is shown in Figure (1). This model has been widely accepted as a tool to synthesize a continuous hydrograph of hourly or daily stream flows at a watershed outlet (Visseman, 1996). The (SWM) is based on the following principles set out by Crawford and Linsley (Al-Mussawi, 2001).

1- The model should represent the hydrologic regimes of a wide variety of streams and rivers with a high order of accuracy.
2- It should easily be applied to different watersheds with existing hydrologic data.
3- The model should be physically relevant, so that estimates of other useful data in addition to stream flow, such as overland flow or actual evapotranspiration, can be obtained.

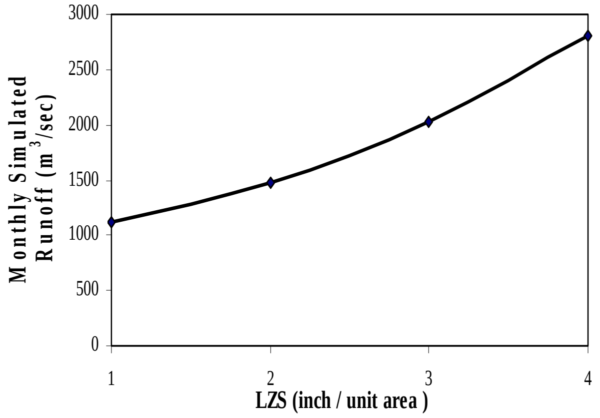

Figure 4: The effect of the parameter (LZS) on monthly simulated runoff

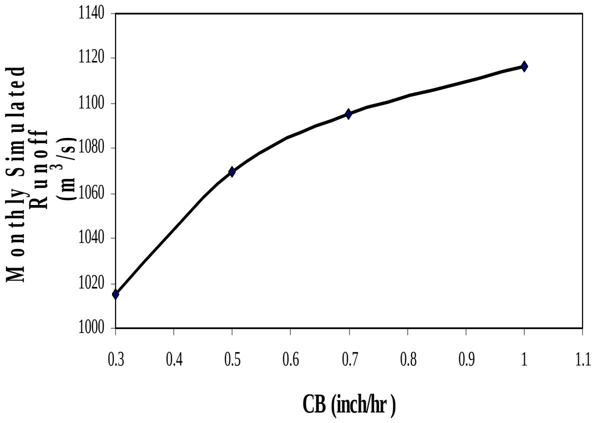

Figure 5: The effect of the parameter (CB) on monthly simulated runoff

Development of Stanford Watershed Model Functions

The Stanford Watershed Model (SWM) is developed by using many equations which are applied to the main program and other subroutines of the program to estimate runoff coefficient each hour during the water year. They involve rainfall intensity, concentration time, return period, curve number and runoff coefficient equation:

Rainfall Intensity

The relation of rainfall intensity used in this study is:

$$I = a/(t + b) \qquad (1)$$

The values of constants **a** and **b** depend on the return period as shown below (Holfelder, 1980).

For **TR=10 years, I=1200/(t+20)** (1 a)

For **TR=5 years, I=1000/(t+20)** (1 b)

For **TR=2 years, I= 700 /(t+25)** (1 c)

Concentration Time (t_c)

The storm duration which will correspond with the maximum rate of runoff is known as the time of concentration or the gathering time. It is defined as the longest time taken for water to travel by overland surface flow from any point in the catchments to the outlet (Hudson, 1981).

$$t_c = k_u \, n^{0.6} L^{0.6} / I^{0.4} S^{0.3} \qquad (2)$$

where;

n=Manning's coefficient.

L= overland flow length, m(ft).

I = rainfall intensity, mm/hr (in./hr)

S=surface slope, m/m (ft/ft).

k_u =empirical coefficient equal to 6.92 (0.933 in English unit) (Brown et al., 2001).

In this study, the rainfall intensity was measured for each hour, therefore the concentration time could not exceed one hour.

Table 1: Imperviousness percent

Urban land – use type	Imperviousness percent
Low-intensity residential type	Impervious surface is very low, usually less than 30% ;population density is less than 500 persons/km^2.
Medium-intensity residential type	Impervious surface is usually greater than 20%; population density is between 500 and 1500 persons/km^2.
High -intensity residential type	Impervious surface is usually greater than 40%; population density is between 1500 and 3000 persons/km^2.
Very-high-intensity residential type	Impervious surface is usually greater than 50%; population density is greater than 3000 persons/km^2.
Commercial, industrial and transportation lands	Impervious surface is usually greater than 60%; population density is very low, usually less than 10 persons/km^2.

Table 2: (MSWM) parameters and their values

Input Parameter	Value
UZS	0.0 – 0.1 – 0.2 – 0.3
LZSN	4.0 – 4.4 – 4.8 – 5.0
LZS	1.0 – 2.0 – 3.0 – 4.0
CB	0.3 – 0.5 – 0.7 – 1.0
SCEP	0.0 – 0.1 – 0.2 – 0.3
EPXM	0.1 – 0.15– 0.2 – 0.3
K3	0.1 – 0.14–0.18– 0.3
K1	1.0 – 1.1 – 1.2 – 1.3

Return Period (TR)

The term (TR) refers to the estimated frequency of rare events .The return period is a statistical matter. For example, if the system is designed for a return period of 10 years, the statistical assumption is that the system will accommodate the most severe storm to occur once in 10 years. It is apparent that the selection of a return period of 25 years instead of 10 years means a more costly system. Conversely, if the frequency is 5 years, the intensity of the design storm will be less and in most cases a less costly drainage system will result (Brown et al., 2001). For storm water drainage structures, conveying runoff resulting from rain events, the return period is taken as 2, 5, 10 years (Holfelder, 1980).

Soil Conservation Curve Number (CN)

The runoff curve number, designated as CN, for the hydrologic soil- cover complexes is functionally related to potential infiltration S1 as (Chaw, 1964):

$$CN=1000/(S1+10) \quad (3)$$

where;

S1= potential infiltration (unit depth), which is equal to the summation of the actual infiltration (F) and the initial abstraction (I_a).

Imperviousness Percent

The imperviousness percent here is divided according to urban land-use types which consist of (low intensity residential, medium intensity residential, high intensity residential, very high intensity residential, commercial, industrial and transportation lands) as shown in Table (1) (Dengsheng and Qihao, 2006).

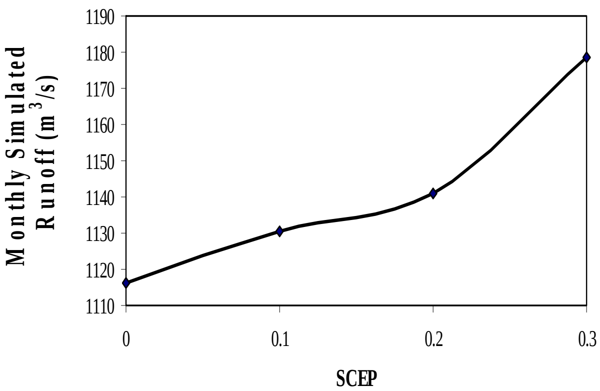

Figure 6: The effect of the parameter (SCEP) on monthly simulated runoff

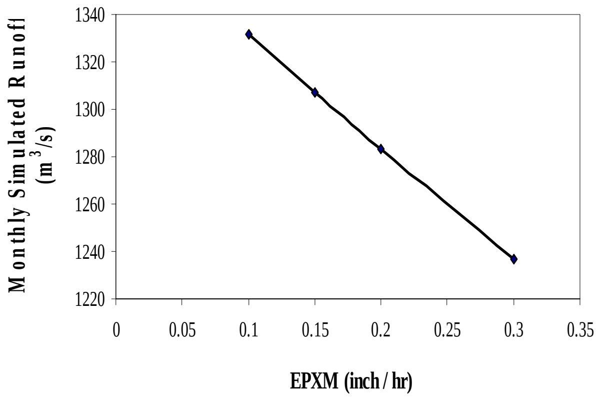

Figure 7: The effect of the parameter (EPXM) on monthly simulated runoff

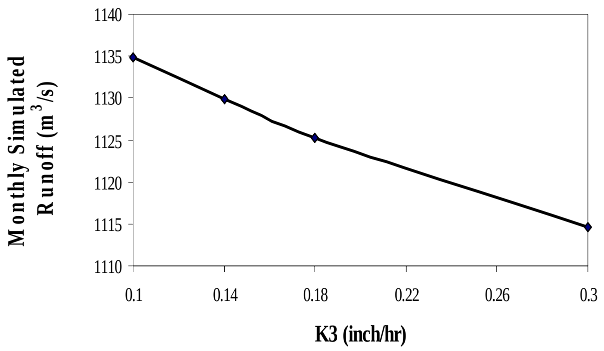

Figure 8: The effect of the parameter (K_3) on monthly simulated runoff

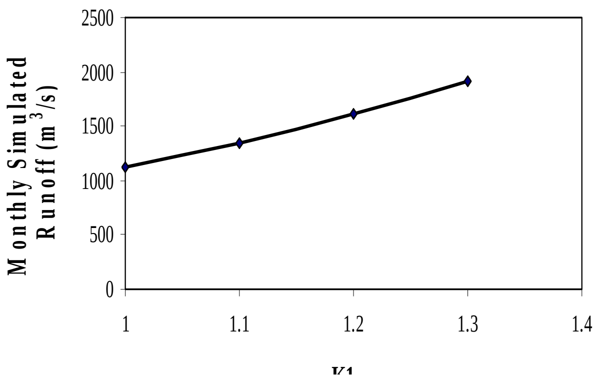

Figure 9: The effect of the parameter (K_1) on monthly simulated runoff

The Runoff Coefficient Equation

The runoff coefficient in the rational formula is dependent on many factors. Tables and graphs generally allow the determination of C from only two or three of these factors. Nomographs and regression equations can provide relations among more factors. Some of these equations are (Visseman, 1996):

$$C11= 7.2\,(10)^{-7}\ CN^3\ TR^{0.05}\ [(0.01\ CN)^{0.6}]^{-s^{0.2}} \quad (4)$$

$$C12= (0.001\ CN^{1.48})^{0.15-0.1I} \quad (5)$$

$$C13= [(IMP+1)/2]^{0.7} \quad (6)$$

$$C=C11 * C12 * C13 \quad (7)$$

where;
CN=SCS curve number,
T R =return period (years),
S =average land slope (%),
I =rain intensity (in./hr),
IMP =percent imperviousness.

General Description of the Studied Catchment

In this study, the Stanford Watershed Model is applied on Al-Adhaim catchments. It lies inside the Iraqi borders, in the southern slopes of the mountain area in the north of Iraq.

Al-Adhaim river is the confluence of four main tributaries; Al-Khasah Jay, Tawook Jay, Kuree Jay and Tuz Jay. It is fed by rainfall only. The total area of Al-Adhaim catchment is 11133 km².

Sensitivity Analysis

Model verification is not complete without comprehensive sensitivity analysis. Once the calibrated parameters are arrived at by a best fit procedure, sensitivity analysis is performed by holding all parameters constant but one and perturbating the last one such that the variation of the objective function (measure of fit between the observed storm hydrograph and the fitted model) can be examined (Ali, 1998).

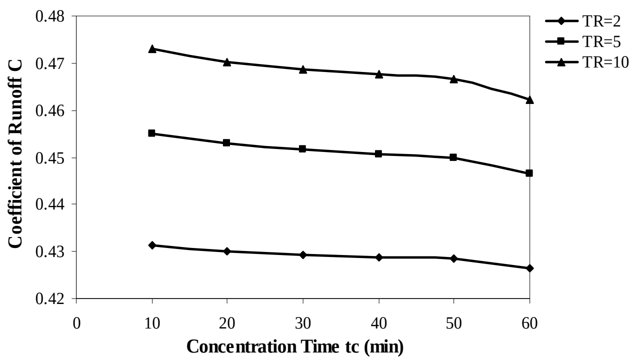

Figure 10: The relationship between runoff coefficient and concentration time for S=1%, IMP=10%

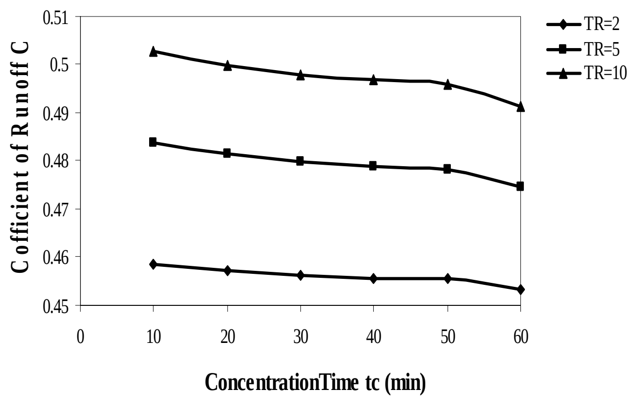

Figure 11: The relationship between runoff coefficient and concentration time for S=1%, IMP=20%

If small perturbations of the parameter produce large changes in the objective function, the system is said to be sensitive to that parameter. This gives a measure of how accurate that parameter must be estimated if the model is to be used in the prediction. If the objective function is not sensitive to the perturbed parameter, then the parameter does not need be accurately estimated in the prediction. If the system is extremely insensitive to the perturbed parameter, the parameter and its associated system components may be redundant and could be deleted from the model (Al-Saa'd, 2008).

Investigation of the sensitivity of model parameters to model performance is an integral and vital part of the modeling process. Sensitivity analysis assists in answering questions concerning the relative importance of the various model components in representing the rainfall-runoff process and the accuracy needed in estimating model parameters on ungauged watersheds.

Modified Stanford Watershed Model (MSWM) Parameters and Their Values

Model parameters involved in the application and their special values are shown in Table (2). Some of these parameters were obtained from field observations and experimentation and the others were obtained from aerial photographs. In addition, the model contains, as mentioned earlier, other coefficients which were obtained by calibration (Al-Saa'd, 2008).

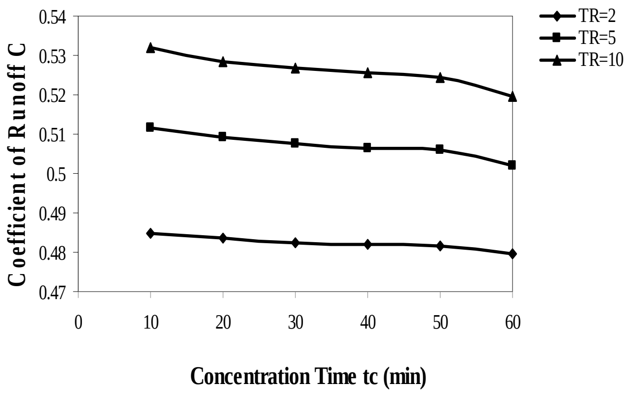

Figure 12: The relationship between runoff coefficient and concentration time for S=1%, IMP=30%

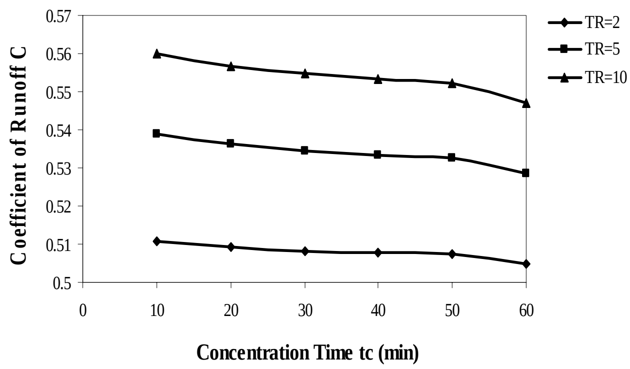

Figure 13: The relationship between runoff coefficient and concentration time for S=1%, IMP=40%

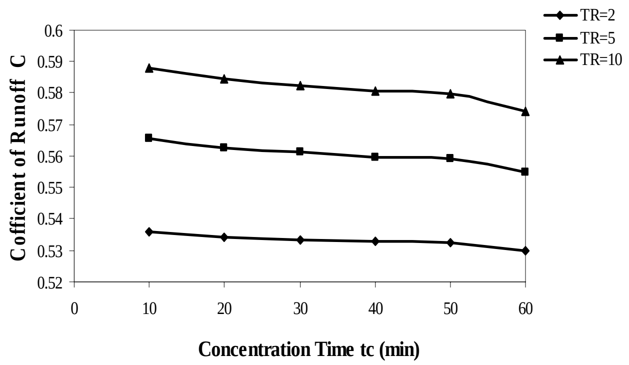

Figure 14: The relationship between runoff coefficient and concentration time for S=1%, IMP=50%

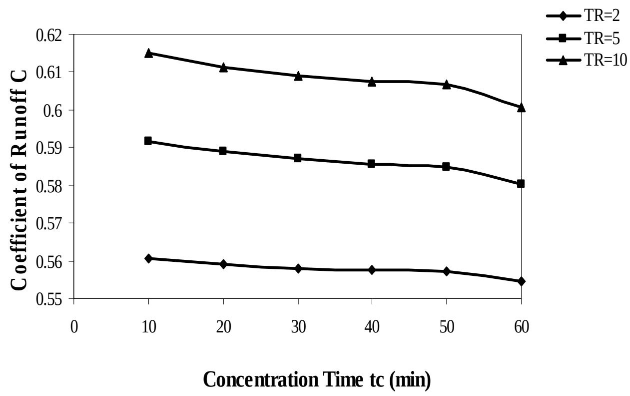

Figure 15: The relationship between runoff coefficient and concentration time for S=1%, IMP=60%

Results of the Application of the Modified Stanford Watershed Model (MSWM) Parameters on Monthly Simulated Runoff and Their Sensitivity

Figures (2) to (9) show the effects of different values of (MSWM) parameters on monthly simulated runoff. These relationships are for (February) of the water year (1983/1984). From these figures, it is clear that:

1- 1-Figure (2) shows the effect of the actual upper zone soil moisture storage (UZS) on monthly simulated runoff. It is clear from this Figure that the rate of monthly runoff increases as the parameter value increases, because the upper soil zone, which may be thought of as at the top few inches of the soil, reacts immediately to rainfall and controls the formation of overland flow.

2- Figure (3) shows the effect of the parameter (nominal lower zone soil storage (LZSN)) on monthly simulated runoff. It is evident from this Figure that the relationship is almost linear. If the value of the parameter increases, the monthly simulated runoff decreases, because infiltration capacity increases as this parameter increases and decreases runoff.

3- Figure (4) shows the effect of the parameter (actual lower zone soil moisture storage (LZS)) on monthly simulated runoff. If the moisture increases in the lower zone, the ground water flow component increases (one of the runoff components). From this Figure, the relationship is seen to be linear. If the value of the parameter increases, the monthly simulated runoff increases, and from the analysis this parameter is sensitive to estimate the runoff.

4- Figure (5) shows the effect of the parameter (infiltration index (CB)) on monthly simulated runoff. The value of monthly runoff increases as the value of the parameter increases, because this parameter represents the infiltration volume, and the relationship is non-linear.

5- Figure (6) shows the effect of the parameter (interception storage volume parameter (SCEP)) on monthly simulated runoff. From this Figure, the relationship is non-linear. If the value of the parameter increases, the monthly simulated runoff increases, because this parameter represents the portion of precipitation that reaches the soil surface by passing through the spaces in the vegetation canopy, and from the analysis this parameter is quite sensitive to estimate the runoff.

6- Figure (7) shows the effect of the parameter (interception storage (EPXM)), which is a function of the type and extent of vegetation on monthly simulated runoff. From this Figure, the relationship is linear. If the value of the parameter increases, the monthly simulated runoff decreases and *vice versa*.

7- Figure (8) shows the effect of the parameter (actual evapotranspiration rate (K3)) on monthly simulated runoff. From this Figure, the relationship is linear. If the value of the of the parameter increases, the monthly simulated runoff decreases and *vice versa*.

8- From Figure (9), it appears that the monthly simulated runoff is very sensitive to the (rainfall adjustment parameter (K1)). From this Figure, the relationship is linear. The value of monthly runoff increases as the value of the parameter increases.

The Relationships between Concentration Times and Runoff Coefficients

The relationships between concentration times and runoff coefficients are studied for variable and constant return periods.

The Effect of Imperviousness

Figures (10) to (15) show the relationship between concentration time (t) and runoff coefficient (C) for a constant value of slope percent (S=1%) and variable values of imperviousness percent and return period. From these figures, the relationships are almost linear and inverse for all return periods due to the inverse relation between the rainfall intensity and the concentration time in equation (1), and the rainfall intensity is directly proportional to runoff coefficient (C) as shown in equation (7).

Runoff coefficient (C) increases when the imperviousness percent increases due to direct proportionality between runoff coefficient (C) and imperviousness percent (IMP) in equation (7).

The Effect of Return Period

Figures (10) to (39) show that the value of runoff coefficient is great for the largest return period due to direct proportionality between runoff coefficient and return period in equation (7).

The Effect of Slope

Figures (10), (16), (22), (28) and (34) show the relationship between concentration time (t^c) and runoff coefficient (C) at a constant value of imperviousness percent (IMP=10%) and variable values of slope percent and return period. From these Figures, the relationships are almost linear and inverse for all return periods due to the inverse relation between the rainfall intensity and the concentration time in equation (1), and the rainfall intensity is directly proportional to runoff coefficient (C) in equation (7).

Runoff coefficient (C) increases with slope percent due to direct proportionality between (C) and (S) in equation (7).

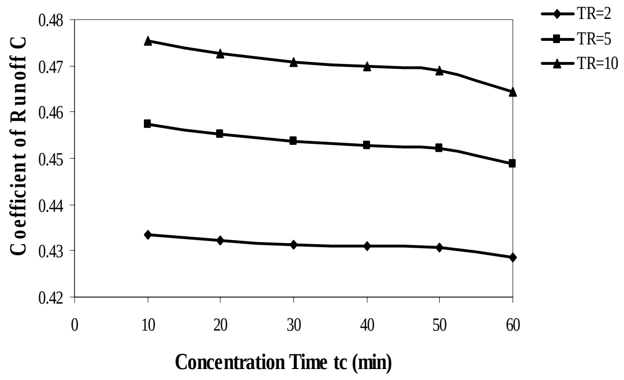

Figure 16: The relationship between runoff coefficient and concentration time for S=2%, IMP=10%

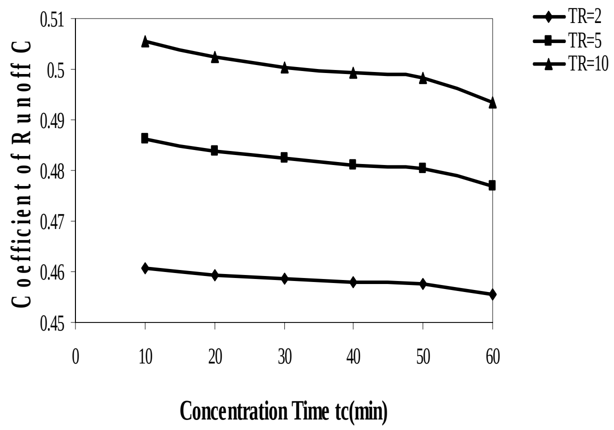

Figure 17: The relationship between runoff coefficient and concentration time for S=2%, IMP=20%

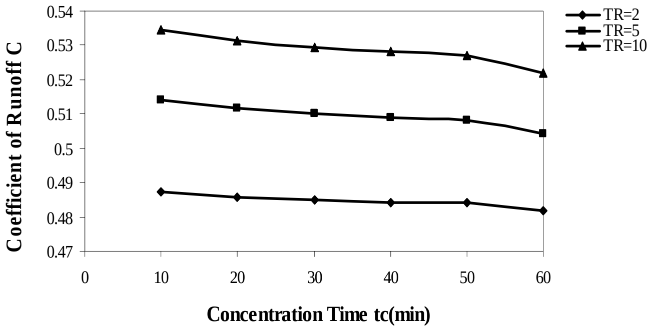

Figure 18: The relationship between runoff coefficient and concentration time for S=2%. IMP=30%

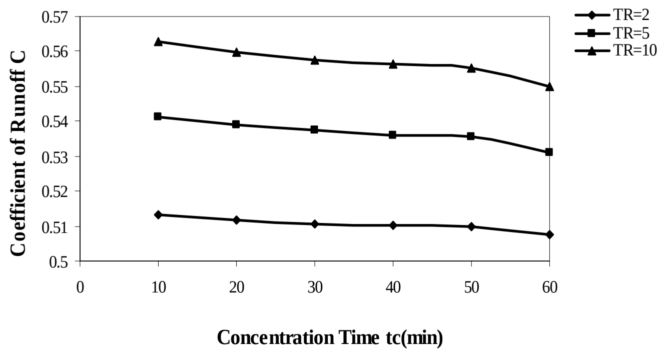

Figure 19: The relationship between runoff coefficient and concentration time for S=2%, IMP=40%

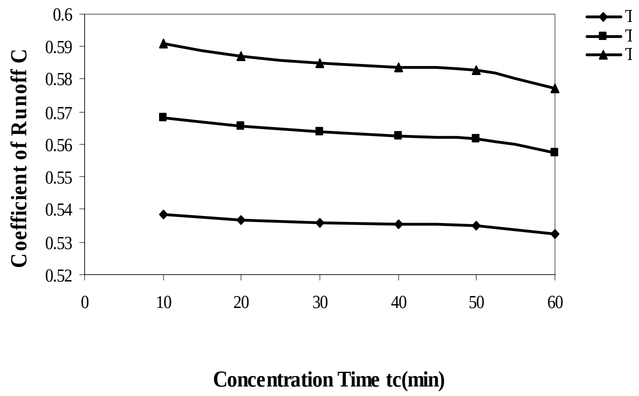

Figure 20: The relationship between runoff coefficient and concentration time for S=2%, IMP=50%

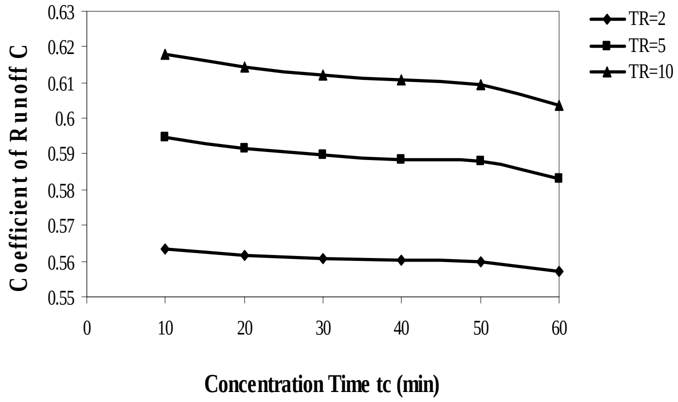

Figure 21: The relationship between runoff coefficient and concentration time for S=2%, IMP=60%

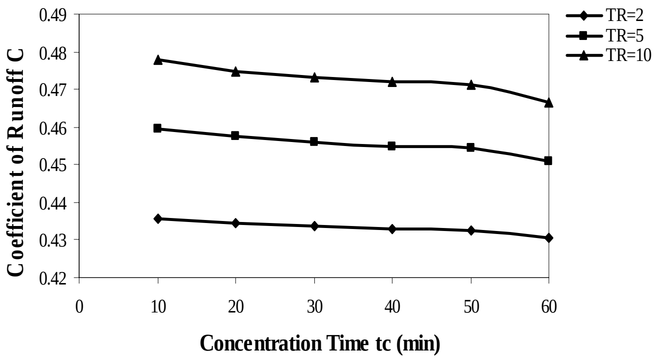

Figure 22: The relationship between runoff coefficient and concentration time for S=3%, IMP=10%

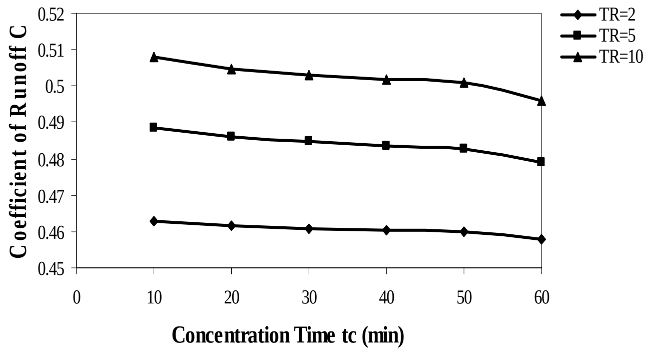

Figure 23: The relationship between runoff coefficient and concentration time for S=3%, IMP=20%

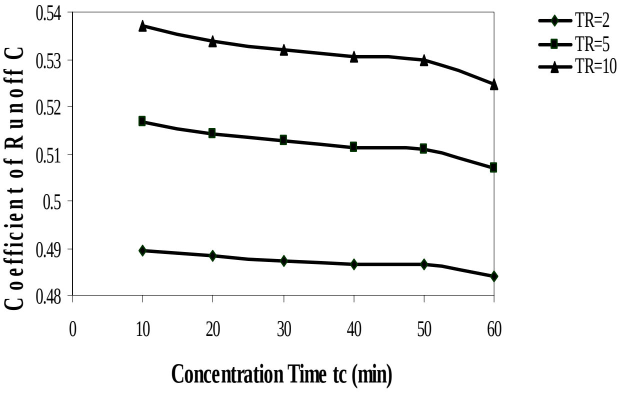

Figure 24: The relationship between runoff coefficient and concentration time for S=3%, IMP=30%

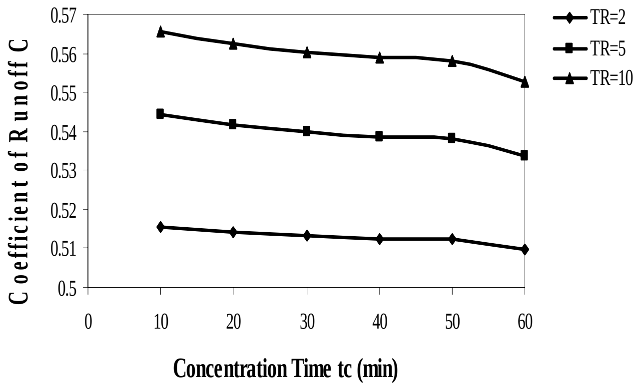

Figure 25: The relationship between runoff coefficient and concentration time for S=3%, IMP=40%

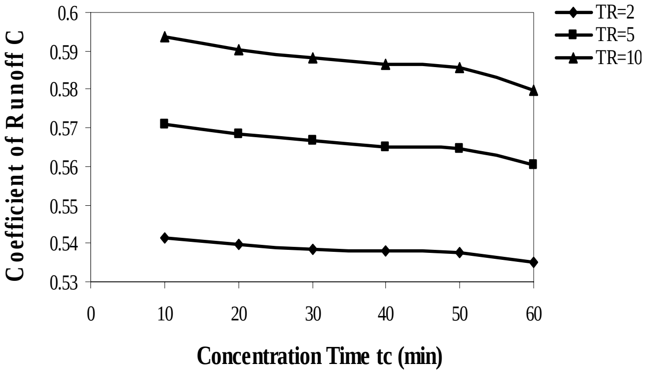

Figure 26: The relationship between runoff coefficient and concentration time for S=3%, IMP=50%

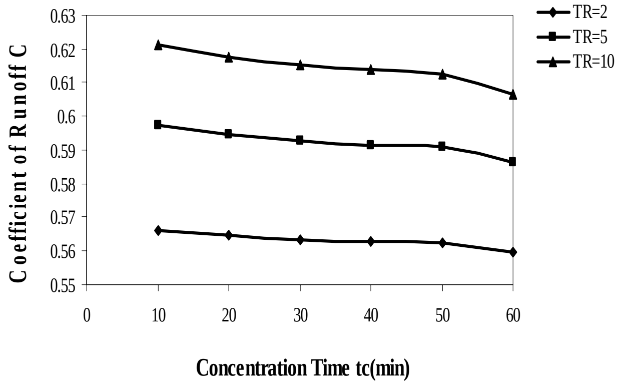

Figure 27: The relationship between runoff coefficient and concentration time for S=3%, IMP=60%

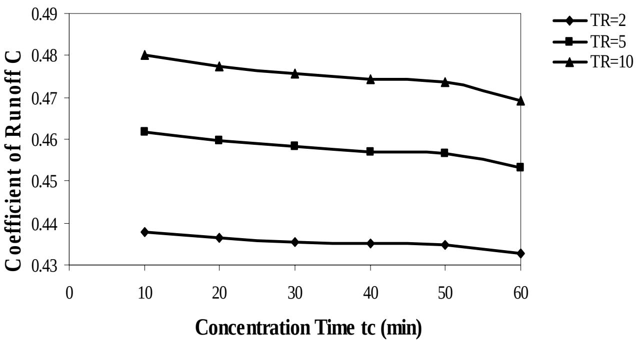

Figure 28: The relationship between runoff coefficient and concentration time for S=4%, IMP=10%

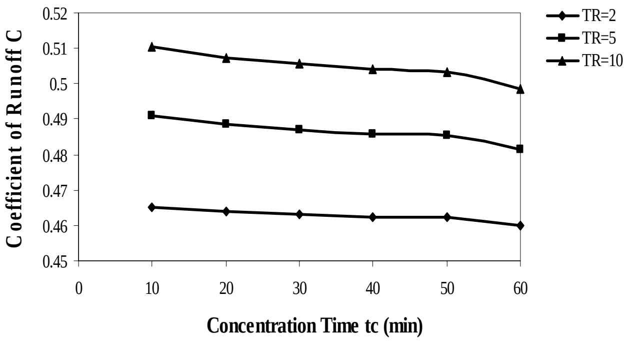

Figure 29: The relationship between runoff coefficient and concentration time for S=4%, IMP=20%

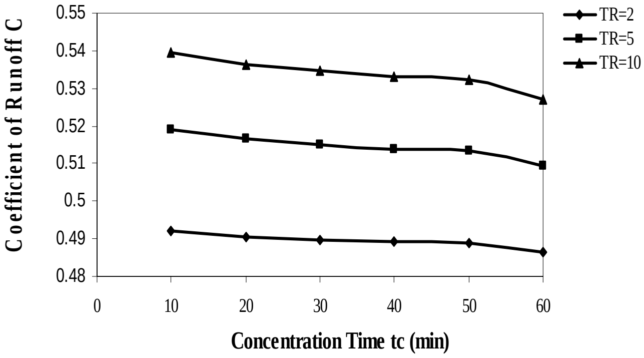

Figure 30:The relationship between runoff coefficient and concentration time for S=4%, IMP=30%

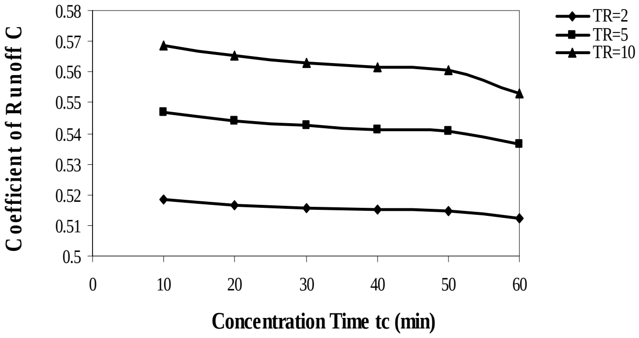

Figure 31: The relationship between runoff coefficient and concentration time for S=4%, IMP=40%

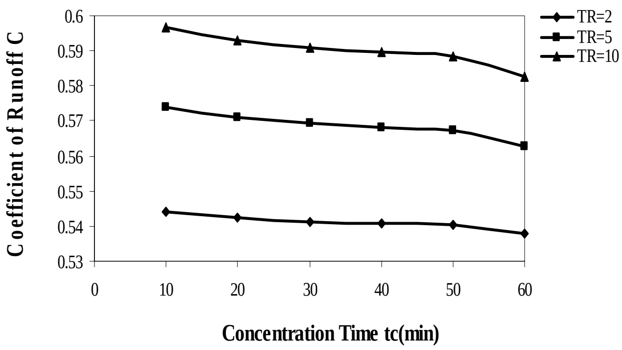

Figure 32: The relationship between runoff coefficient and concentration time for S=4%, IMP=50%

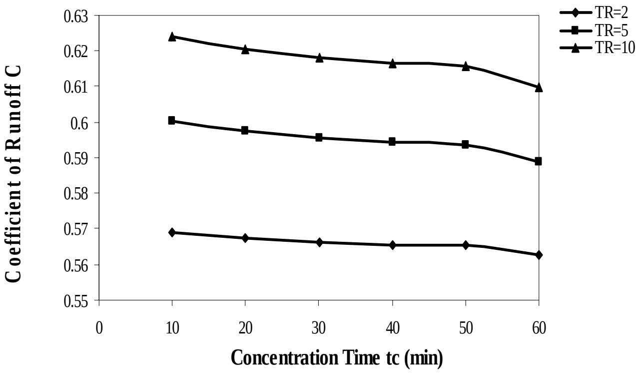

Figure 33: The relationship between runoff coefficient and concentration time for S=4%, IMP=60%

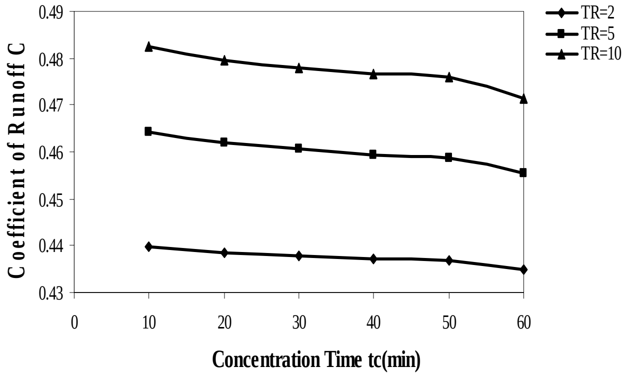

Figure 34: The relationship between runoff coefficient and concentration time for S=5%, IMP=10%

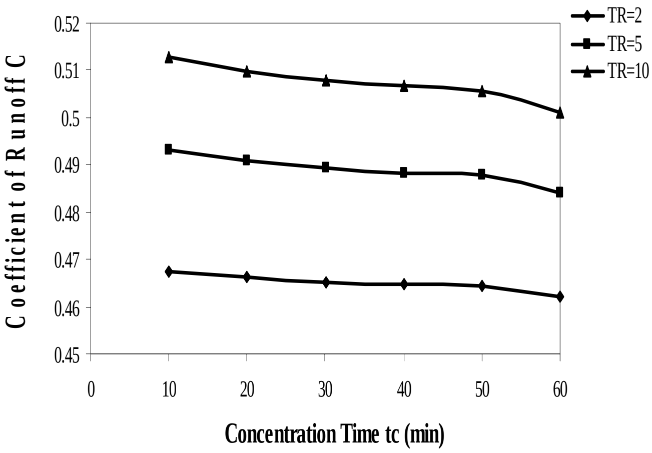

Figure 35: The relationship between runoff coefficient and concentration time for S=5%, IMP=20%

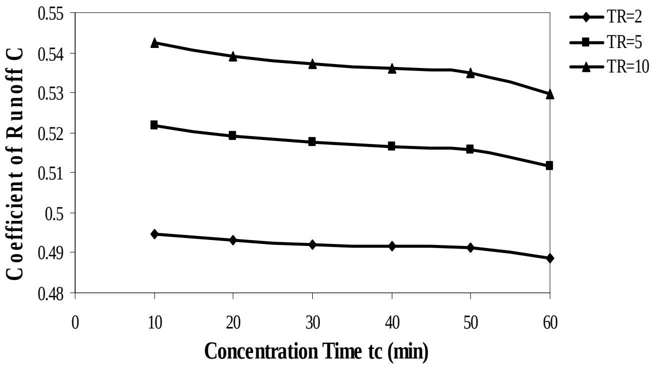

Figure 36: The relationship between runoff coefficient and concentration time for S=5%, IMP=30%

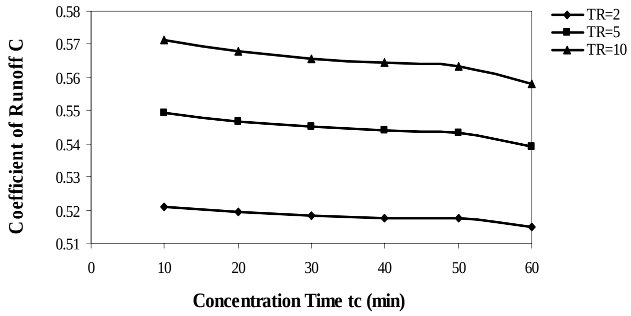

Figure 37: The relationship between runoff coefficient and concentration time for S=5%, IMP=40%

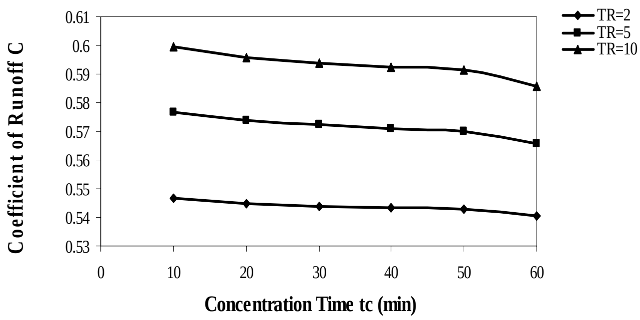

Figure 38: The relationship between runoff coefficient and concentration time for S=5%, IMP=50%

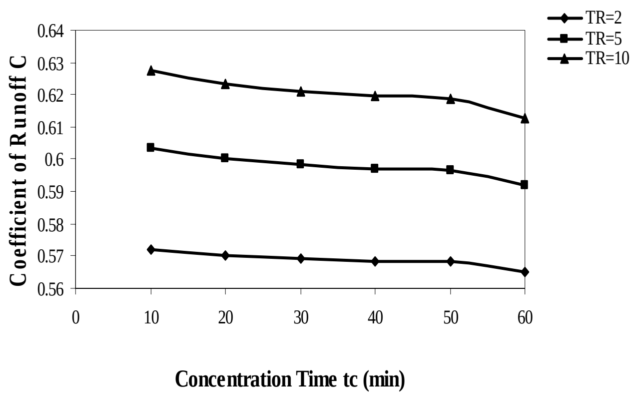

Figure 39: The relationship between runoff coefficient and concentration time for S=5%, IMP=60%

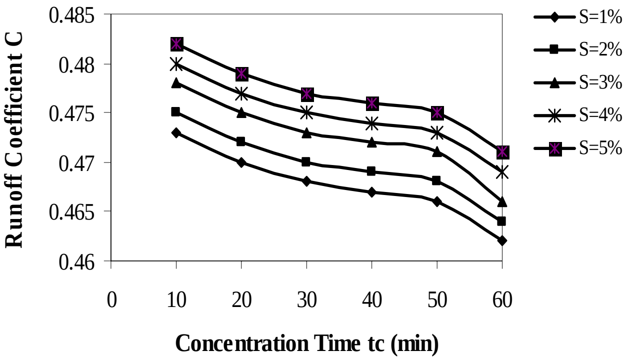

Figure 40: The relationship between runoff coefficient and concentration time for TR=10, IMP=10%

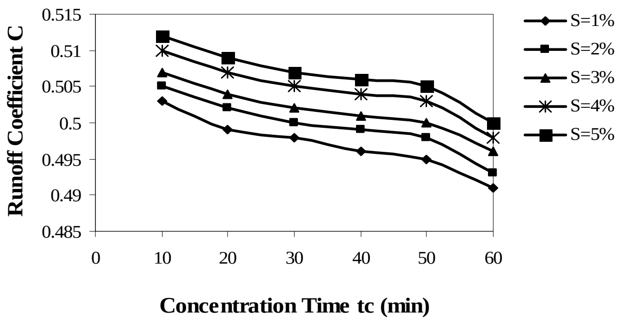

Figure 41: The relationship between runoff coefficient and concentration time for TR=10, IMP=20%

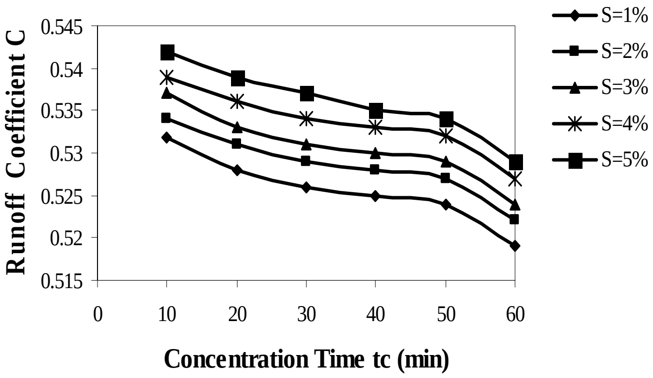

Figure 42: The relationship between runoff coefficient and concentration time for TR=10, IMP=30%

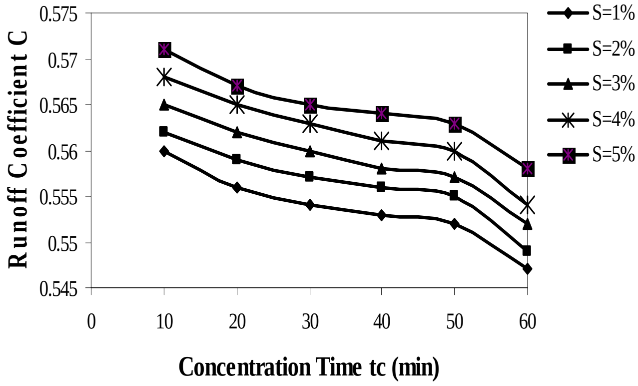

Figure 43: The relationship between runoff coefficient and concentration time for TR=10, IMP=40%

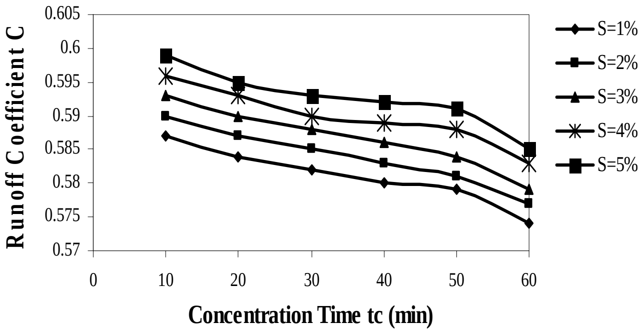

Figure 44: The relationship between runoff coefficient and concentration time for TR=10, IMP=50%

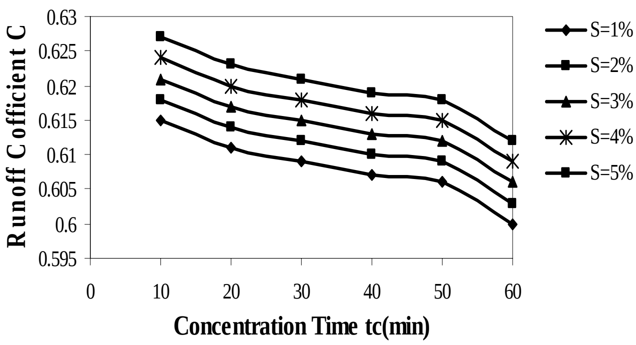

Figure 45: The relationship between runoff coefficient and concentration time for TR=10, IMP=60%

Constant Return Period

Figures (40) to (45) show the relationships between concentration times and runoff coefficients for fixed values of return periods and different slopes. Slope percent varies between 1% and 5%, and the return period is constant for all the relationships (TR=10 years), while the imperviousness percent varies between 1% and 6%. The relationships are non-linear and inverse for all the slope percents, due to the inverse relation between the rainfall intensity and the concentration time in equation (1), and the rainfall intensity is directly proportional with runoff coefficient (C) in equation (7).

The importance of runoff curves can be explained, for example, by the comparison between runoff coefficient values from tables depending on land use only and the values from curves.

CONCLUSIONS

Based on the results presented in this study, the following conclusions can be drawn within the limitations of the studied cases.

1- Digital simulation model proved to be an effective and powerful tool for simulating runoff.

2- Runoff curves give a better and more accurate estimate for runoff coefficient than tables. For example: C=0.51 from curves, but C=0.5-0.7 from tables.

3- Runoff coefficient is directly proportional to slope percent and imperviousness percent.

4- The value of runoff coefficient is great for the largest return period.

5- There are inverse relationships between runoff coefficients and concentration times under the effect of different variables, such as imperviousness percent and slope percent.

6- The results of the sensitivity analysis of the Modified Stanford Watershed Model (MSWM) on monthly simulated runoff rates show: a) a quite sensitive model to actual upper zone soil moisture storage parameter(UZS), b) a medium sensitive model to nominal lower zone soil storage parameter (LZSN), c) a medium sensitive model to actual lower zone soil storage parameter (LZS), d) a quite sensitive model to infiltration index (CB), e) a quite sensitive model to interception storage volume parameter (SCEP), f) a medium sensitive model to interception storage parameter (EPXM), g) a quite sensitive model to actual evapotranspiration rate parameter (K3), h) a very sensitive model to rainfall adjustment parameter (K1).

7- Using the values of runoff coefficients from curves instead of tables, gives more accurate results.

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