REVISITING THE KIRPICH FORMULA USING RAINFALL SIMULATOR EXPERIMENTS

A DISSERTATION

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation entitled "**Revisiting the Kirpich formula using rainfall simulator experiments**" in the partial fulfillment for the award of the degree of Master of Technology in Hydrology, submitted in the Department of Hydrology, Indian Institute of Technology Roorkee, is an authentic record of my work done during the period from June 2015 to May 2016 under the guidance of Dr. Sumit Sen, Assistant Professor, Department of Hydrology, Indian Institute of Technology Roorkee.

The matter embodied in this dissertation has not been submitted by me for award of any other degree.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

In this study, experimental investigation of overland flow time parameters was carried out at varying surface slopes (0.5% to 3%), antecedent soil moisture (8% to 28%) and rainfall intensity (45mm/hr to 90mm/hr). Thirty five experiments were conducted using Advanced Hydrologic System (Rainfall simulator) by generating rainfall on an overland flow plane of area 2 m^2 (2m x 1m). A regression analysis was conducted to develop model for determining the time of concentration. It has been found that majority of the existing empirical models available in the literature under-predict the time of concentration. Specifically, this study showed that the Kirpich equation under-predicted the time of concentration by 10 times. This variation can be attributed to the fact that different models were developed under different conditions. Further, these empirical models are based on different definitions of time of concentration. Results further reveals that Kirpich has given high significance to the slope parameter whereas this study showed that the slope is the least significant parameter. Also the existing models available in the literature do not contain antecedent soil moisture (θ) parameter which has a significant role to play in determining the time of concentration. Models such as Mathur and Perumal (2007) and Izzard (1946) were showing good results at low values of antecedent soil moisture content as compared with the observed data of this study.

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LIST OF ABBREVIATIONS

A = Area

C = Runoff coefficient

CN = Curve number

Cr = Retardance coefficient

G = Constant= 0.01947

i = Rainfall intensity (mm/hr)

K = Constant

k = Kirpich adjustment factor

L = Overland flow length (meters)

n = Manning's coefficient

P_c = Critical rainfall intensity

Q_P = Peak discharge (cumecs)

S = Surface slope (m/m)

T_b = Time of beginning (minutes)

T_C = Time of concentration (minutes)

T_P = Time to peak (minutes)

θ =Antecedent moisture content (m^3/m^3)

Chapter 1 INTRODUCTION

1.1 GENERAL

The design runoff volume to be assessed at the outlet of a watershed involves a prior estimation of the time of concentration (T_C) for a given design rainfall intensity. Time of concentration has been defined as the time required for a drop of water to travel from the most remote part of a watershed to reach the outlet. Hence, T_C is the maximum time during which a whole watershed contributes runoff to reach the watershed outlet. This definition assumes that there is a uniform and continuous rainfall occurring over the entire watershed for a period equal to T_C. The product of T_C and the uniform effective rainfall intensity gives the total maximum runoff volume in depth units. The product of intensity of rainfall, runoff coefficient and the watershed area gives the peak discharge.

The concept of T_C was first introduced by Mulvany (1851) as the time at which a discharge reaches its peak for a uniform intensity of rainfall. Kuichling (1889) determined T_C using hydrograph analysis and stated that for a given drainage area discharge increases with time until it reaches T_C. Hicks (1942) determined T_C as the time between the beginning of a rainfall and the time at which rainfall reaches its equilibrium discharge. Izzard (1946) defined T_C as the time between the beginning of a rainfall to the time at which the rainfall reaches 97 percent of equilibrium discharge. Su and Fang (2004) defined T_C as the time between the beginning of effective rainfall to the time at which the rainfall reaches 98 percent of equilibrium discharge.

1.2 OVERLAND FLOW

Overland flow is the beginning of the hydrological runoff process by which the precipitation fallen on a land surface is transported down the slope as a thin sheet of flow before draining into streams (Woolhiser, 1981). There are two mechanisms by which overland flow can be generated: (1) Saturation-excess (Dunne and Black, 1970) and (2) Infiltration-excess (Horton, 1933). In saturation-excess (or Dunne’s overland flow), the cumulative infiltration depth exceeds the soil storage capacity and the resulting excess spills onto the surface as overland flow. Dunne’s overland flow generally occurs in areas of shallow water table. In infiltration- excess (or Hortonian overland flow), the rainfall rate exceeds infiltration capacity and this excess rainfall moves as overland flow. Hortonian overland flow generally occurs in areas where water table is deep.

1.3 PEAK DISCHARGE ESTIMATION

If a rainfall occurs over an impervious surface at a constant rate, the resultant runoff from the surface would finally reach a rate equal to the rainfall. However, in the beginning, only a certain amount of water will reach the outlet, but after some time, the water will start reaching the outlet from the entire area. In this case, the runoff rate would become equal to the rate of rainfall. Thus, by definition, the period after which the entire area will start contributing to the runoff is called T_C. The runoff resulting from a rainfall event having a duration lesser than T_C will not be maximum, as the entire area will not be contributing to the runoff. Further, it has been established that the maximum runoff will be obtained from the rain having a duration equal to T_C, and this is called the critical rainfall duration. Based upon these basic principles, the rational formula was evolved, due to the efforts of Fruhling of Germany, Kuichling of America, and later Lloyd Davis of England. This formula states that

$$Q_P = (1/36)C*p_c*A$$

where, Q_P = Peak discharge (m^3/sec), C = Runoff coefficient, p_c = Critical rainfall intensity (cm/hr), and A = Area (hectares).

1.4 FACTORS AFFECTING PEAK DISCHARGE

Coefficient of runoff

The coefficient of runoff (C) is in fact, the impervious factor of runoff, representing, the ratio of runoff to precipitation. The value of C increases as the imperviousness of the area increases, thus tending to make C=1 for perfectly impervious areas.

Intensity of Rainfall

A rainfall at a place can be completely described if its intensity, duration and frequency is known. The intensity of a rainfall is the rate at which it is falling, the duration is the time for which it falls with that given intensity, and frequency is the number of times it falls.

Time of concentration

The time of concentration generally consists of two parts:

(1) The inlet time or overland flow time or time of equilibrium (T_i) i.e. the time taken by the water to flow overland from the critical point upto the point where it enters the drain mouth.

(2) The channel flow time (T_f) i.e. the time taken by the water to flow in the drain channel from the mouth to the considered point. This may be obtained by dividing the length of the drain by the flow velocity in the drain.

The total time of concentration (T_C) at a given point in the drain, for working out the discharge at that point, can be obtained as:

$T_C = T_i + T_f$

Areal distribution factor

It is a well established fact that the intensity of rainfall recorded at a particular rain gauge station in a catchment is not the same throughout the catchment. As the size of the catchment increases, the average intensity of rainfall over a catchment as a whole goes on decreasing compared to the point intensity recorded at a particular station. Therefore, the areal distribution factor, also called, the dispersion factor, is always applied to the point of rainfall for working out the design rainfall intensity.

The value of critical rainfall intensity (p_c) can be calculated as:

$P_c = a/ (T_C+b)$

where, a and b are constants.

1.5 KIRPICH EQUATION

The Kirpich equation, developed in 1940 by Z.P. Kirpich is one of the oldest and probably the most widely recognized equation to calculate the T_C in a watershed. Time of concentration is used to compute the peak discharge in a watershed. The peak discharge depends on the rainfall intensity, which is based on T_C. The time of concentration calculation using the Kirpich equation depends on the length of the longest watercourse (L), average slope of the watershed (S), and a coefficient which depends on the type of ground cover.

Assuming the rainfall intensity to be uniform and without considering the effect of antecedent soil moisture content, the Kirpich equation was developed from data obtained in seven rural watersheds in Tennessee (USA) (Table 1.1). The watersheds were characterized by well-defined divides and drainage channels, the topography being quite hilly. This equation is used widely used in urban areas for overland flow. Assuming uniform rainfall intensity over a watershed, Kirpich proposed the T_C estimation formula for small watersheds expressed as:

$T_C = G\ k\ (L / S^{0.5})^{0.77}$

Table 1.1 Kirpich adjustment factor (k) for different ground covers

Ground Cover	**Kirpich Adjustment Factor, k (Chow et al., 1988; Chin, 2000)**
Overland flow on bare soil	1.0
Overland flow on natural grass	2.0
Flow in concrete channels	0.2
Overland flow on asphalt surfaces	0.4

1.6 FACTORS AFFECTING KIRPICH EQUATION

Length of the watercourse (L)

The length of travel is one of the two factors that affect the T_C calculation using the Kirpich equation. Time of concentration varies directly with the length of travel i.e. as the length of travel increases, T_C also increases. The exponent of length taken in Kirpich equation is 0.77.

Slope of the watercourse (S)

According to the Kirpich equation, slope has a significant effect on T_C. Time of concentration varies inversely with the slope of the watercourse i.e. as the slope increases, T_C decreases. The exponent of slope taken in Kirpich equation is -0.385.

1.7 LIMITATIONS OF KIRPICH EQUATION

The Kirpich equation has certain limitations:

(1)It is valid for slopes ranging between 3 to 10% and

(2)It is valid for areas ranging between 1 to 112 acres.

1.8 OBJECTIVES

The objectives of this study are:

- To estimate the validity of Kirpich equation for slopes less than 3% under different rainfall intensities.
- To develop an equation for time of concentration using rainfall simulator experiments.
- To compare the observed experimental results with the various commonly used empirical time of concentration equations.

Chapter 2 REVIEW OF LITERATURE

2.1 TIME OF CONCENTRATION ESTIMATION METHODS

Time of concentration (T_C) estimation methods can be classified into two major types (Wong 2009): (1) lumped methods, and (2) distributed methods. In lumped methods, T_C of a watershed is estimated using some formula. Most empirical methods, that are developed using regression analysis, such as the Kirpich (1940) method, fall in this category. In distributed methods, the overland flow times are calculated individually and then summation of each flow times gives the T_C. Distributed methods such as the NRCS (Natural Resource Conservation Service) (1986) velocity method requires a relatively larger number of parameters and generally give better estimations of T_C (Yen 1982; Kibler and Aron 1983).

The primary issue in evaluating T_C estimation methods is that the true value of T_C cannot be directly determined or measured. Since T_C is influenced by variations of rainfall characteristics, topography, and channel characteristics. Hence, the first step is to identify the most proper estimation method which can give accurate estimations of T_C. Various empirical and semi-empirical methods for determining T_C are shown in Table 2.1.

The most comprehensive model to predict T_C summarized from more than 10 models by Papadakis and Kazan (1987) included four independent variables:

• Length of the watershed,

• Surface roughness (usually Manning's n),

• Slope of the watershed, and

• Rainfall intensity.

The model is expressed as:

$T_C = KL^a n^b S^{-y} i^{-z}$

This equation exhibits a linear correlation of the logarithms of the variables involved.

Researchers (Akan 1986, Meyles 2003, Li and Chibber 2008) found that the antecedent soil moisture (θ) appeared to influence the runoff travel time. Using the above model as the baseline model researchers added the antecedent soil moisture variable to create a new model. It is expressed as:

$T_C = KL^a n^b \theta^{-x} S^{-y} i^{-z}$

Table 2.1Empirical and Semi-empirical T_C Estimation Methods

Method	Equation for T_C	Remarks
Kirpich (Tennessee) (1940)	$T_C = GkL^{0.77}S^{-0.385}$	Area from 1–112 acres (0.40 to 45.3 ha) and Slopes from 3 to 10%.
Hathaway (1945), Kerby (1959)	$T_C = 1.44(nL)^{.467}S^{-.233}$	Watersheds of less than 10 acres and slopes less than 1% and Manning's n value were 0.8 and less.
Morgali and Linsley (1965), Aron and Erborge (1973)	$T_C = 0.94L^{0.6}n^{0.6}S^{-0.3}i^{-0.4}$	Overland flow equation developed from kinematic wave analysis of runoff from developed surfaces.
FAA (1970)	$T_C = 3.26(1.1\text{-}C)L^{0.5}S^{-0.333}$	Valid for small watersheds where overland and sheet flow dominate.
Izzard (1946)	$T_C = 202.75(.0007i+Cr)L^{0.33}S^{-0.33}i^{-0.66}$ where, Cr = Retardance coefficient	Hydraulically derived formula; Value of Cr for fine sand is 0.0075
Papadakis and Kazan (1987)	$T_C = 4.09L^{0.50}n^{0.52}S^{-0.31}i^{-0.38}$	Developed from data obtained by84 rural watersheds with areas less than 5 km^2, and experimental data from US Army corps of Engineers.
Natural Resources Conservation Service (1997)	$T_C=0.0526[(1000/CN)-9]L^{0.8}S^{-0.5}$	For small rural watersheds.
Mathur and Perumal (2007)	$T_C=18.75i^{-0.27}[nL/\sqrt{S}]^{0.31}$	For small watersheds

2.2 FACTORS AFFECTING TIME OF CONCENTRATION

2.2.1 INTENSITY OF RAINFALL

McCuen et. al., (1984) after comparing 11 T_C methods using data collected from 48 urban watersheds, found that the rainfall intensity is the most important input parameter for the estimation of T_C. Saghafian and Julien (1995) demonstrated that T_C varies inversely with rainfall intensity raised to the power 0.4. The formulas that does not account for rainfall intensity are valid only for limited range of rainfall intensities (Wong 2005).

2.2.2 SURFACE SLOPE

Liu et. al., (2003) developed a two-dimensional kinematic wave model for simulating runoff generation and flow concentration on an experimental infiltrating hill slope receiving artificial rainfall. Experimental observations were done for runoff generation and flow concentration on hill slopes with irregular topography. Researchers (Liu et. al., 2003) demonstrated that the direction and flow lines of overland flow are controlled by the topography of the slope surface. The time of concentration varies inversely with the surface slope. The ratio of surface slope to random roughness is a significant variable (Darboux et. al., 2001).

2.2.3 SURFACE ROUGHNESS

Wong and Chen (1997) highlighted that for a plane that is sufficiently long, from upstream to downstream of a plain, the flow regime may change from laminar to transitional to turbulent. Sellin et al. (2003) concluded that for vegetated flood plain a single Manning's *n* roughness coefficient is inappropriate, it depends upon flow depth, velocity, vegetation type, density, dimensions, and flexibility which in turn depend upon age and season. So in the end it becomes necessary to choose an optimum/appropriate value for the Manning's *n*.

2.2.4 INFILTRATION

Infiltration has a significant effect on T_C (Hjelmfelt 1978). The rainfall rate has to exceed the infiltration capacity of the soil for the generation of overland flow, so for the same rainfall rate T_C can vary significantly based on the surface infiltration curve. Akan (1986) developed a mathematical formula based on kinematic overland flow and Green-Ampt infiltration, using Manning's roughness coefficient for calculation of T_C on a rectangular plane surface. Paintal (1974) also found that T_C is governed by infiltration.

2.2.5 DEPRESSION STORAGE

Onstad (1984) calculated depressional storage volumes for over 100 plots from microrelief data. Results demonstrated that the runoff begins before the depression storage is completely filled. Hence, the amount of rainfall excess needed to fill depressions is larger than the depression volume. Paintal (1974) reported T_C to be affected by depression storage. During any rainfall event, whenever the rainfall intensity exceeds the infiltration capacity of the soil, depressions on the surface begins to fill. A part of the rainfall that stays on surface ultimately either evaporates back into the atmosphere or infiltrates. Various studies have been done to investigate the effect of this hydrological process on overland flow generation.

Contrary to the belief that runoff begins after all depressions are filled; Hansen (2000) found that runoff starts before all the depression storage is filled. He found that location of depressions also have a decisive influence on the precipitation excess required to all depressions.

2.2.6 ANTECEDENT MOISTURE CONTENT

Akan (1986) stated that the others factors (such as rainfall intensity, manning's coefficient, length of plot, surface slope) remaining the same, T_C increases with decreasing antecedent moisture content. Merz and Plate (1997) showed that organization in spatial patterns of soil moisture and soil properties may have a dominant influence on the catchment runoff. Meyles et. al., (2003) found that the antecedent moisture content influences the shape of a resulting hydrograph for a storm event.

2.3 BRIEF REVIEW

Gericke and Smithers (2014) highlighted that substantial errors in the estimation of peak discharge may be due to errors in the determination of overland flow time. The time parameters that are frequently used to express overland flow time are T_C, lag time (T_L), and time to peak (T_P). Researchers compared different overland flow time parameter estimation models with the models recommended for South Africa and found that the available models should not be used beyond their original developmental regions without any local correction factors.

Almeida et. al., (2014) used thirty empirical methodologies for the estimation of T_C. The hierarchical cluster analysis (Cluster) was applied in order to assess the similarity degree among the selected methodologies. Researchers concluded that there is a behavioural variability among the studied methodologies for the estimation of T_C. Regular and intensive hydrological monitoring is necessary to select the proper estimation methodology to measure T_C in river basins.

KC and Fang (2013) conducted experimental investigation on a concrete plot of 0.25 percent slope to collect rainfall-runoff data. It was found that the available empirical models predict large values of T_C, as the slope tends to zero. Researchers generated T_C data for varying slopes using a quasi-two-dimensional dynamic wave model. This generated T_C data was used for developing T_C regression equation for estimating improved time of concentration on low sloped planes.

Kemble et. al., (2012) conducted laboratory experimental investigation on advance hydrological system to generate runoff hydrograph data. A V-catchment system was placed over the advance hydrological system and hydrographs were generated for varying slopes and intensities of rainfall. Researchers conducted experiments using two types of overland flow roughness conditions formed on a (1) acrylic sheet surface placed over the V- catchment and (2) sand paper for generating artificial roughness on a V-catchment surface. The approximate convection-diffusion (ACD) model was used to simulate the hydrographs generated from the experiments. Researchers demonstrated that the approximate convection-diffusion model was able to reproduce the experimental hydrographs with Nash-Sutcliffe efficiency greater than 90 percent.

Grimaldi et. al., (2012) found that available approaches in the literature for the estimation of T_C can give values that may differ from each other by upto 500%.

Sharifi and Hosseini (2011) highlighted that a vast number of approaches available in the literature and their unspecified performances have often bewildered in choosing the most suitable T_C estimation approach. Researchers found that if appropriate modification factor is inserted into T_C estimation formulas, the uncertainty in the estimation of T_C will be reduced to a good extent.

Chakravarti and Jain (2010) conducted laboratory experiments on advance hydrological system to study the overland flow characteristics for different slopes and intensities of rainfall. A sand bed was prepared for using it as overland flow plane. A one- dimensional kinematic wave model for overland flow routing was developed to study the effect of slope and rainfall intensity on overland flow roughness. Researchers found that the numerical model simulates the rising limb and steady state limb of the observed hydrograph very well, but considerable differences were observed in lower part of recession limb due to release of water from sand bed. It was also demonstrated that for a given rainfall intensity, an increase in the overland plane, reduces the time to peak. For a given rainfall intensity, the resistance to flow decreases with an increase in the overland plane slope, however, for a given slope, the resistance to flow decreases with an increase in rainfall intensity.

McCuen (2009) found that because of differences in slope, flow depth and roughness in most parts of the watershed, uncertainty arises in the estimation of T_C. When T_C is used to estimate a peak discharge, an under-estimate of T_C will result in the over-prediction of the discharge. Hence, to obtain accurate peak discharge estimates, computed T_C must be accurate.

Li and Chibber (2008) conducted laboratory experiments using a mobile artificial rainfall simulator to measure overland flow times on surfaces with very low slopes. Researchers developed a regression model for predicting the overland flow time. The predicted regression model was then compared with the available empirical and semi-empirical approaches in the literature for calculation of T_C. Researchers found that most of the available models in the literature under-predict the overland flow time. The cause for this problem is occurrence of slope in the denominator in the most of the existing T_C models. Time of concentration increases to infinity, as the slope inclines to zero. It was also found that that the antecedent moisture content has a significant role in estimation of T_C, which is not include in the existing models.

Bennis et. al., (2007) developed a model for runoff simulation for small-scale built up catchments. This model was based on the improvement of rational hydrograph approach and examines the part played by impervious and pervious areas, the variability of rainfall with respect to time, the infiltration on pervious areas and the initial abstraction on impervious areas. The improved rational hydrograph approach was applied to 10 rainfall events gauged in two different urban catchments. A comparison was made between the improved rational hydrograph approach with the calculated runoff. Research achieved a fine consensus between observed and simulated runoff hydrographs.

Mathur and Perumal (2007) developed a regression relationship between T_C and characteristics of watershed and rainfall. The time of concentration of the harvested rainwater in a watershed was estimated based on the step-wise regression relationship developed using the watershed area, channel length, roughness coefficient, channel slope, overland slope, and effective rainfall intensity. Six different regression relationships linking T_C with the watershed and rainfall characteristics were studied based on 80 sets of runoff generation events simulated using the HEC-HMS model on the basis of kinematic wave theory. Using 42 sets of independent rainfall-runoff events generated on hypothetical V-shaped watersheds, the best regression relationship was identified and it was expressed as:

$$T_C=18.75i^{-0.27}[nL/\sqrt{S}]^{0.31}$$

Meyles et. al., (2003) conducted experiments to measure the spatial and temporal variations in moisture content in the soil profile. The experiments were performed at a hill slope scale in a small-scale headwater catchment in southeast Dartmoor, UK, in order to evaluate how the spatial profile affects the generation of runoff. Researchers found that during the dry state, the catchment response was relatively small and the stream discharge was relatively small for most rainstorms. During the wet state, storms resulted in notably higher rates of discharge and the area producing the runoff enlarged to 65 percent of the area. Researchers also found that the antecedent moisture content influences the shape of a resulting hydrograph for a storm event.

Wong (2002) on the basis of rainfall simulation experiments on concrete and artificial grass surfaces, for a net uniform rainfall and a single plane coupled the Darcy-Wiesbach friction formula with the kinematic wave T_C formula to get kinematic-Darcy-Wiesbach T_C formula.

Romkens et. al., (2002) conducted the study in a steady state flow regime to which sediment was added at a controlled rate at the upstream of a 7m long and 10m wide channel of about 1% slope steepness. As the sediment addition rate was increased, sediment movement by siltation gives way to an organized structure consisting of a strip that transition into a meandering bed form.

Willems (2001) stated that for both field and laboratory studies, rainfall simulation facilitate control of both the temporal and spatial features of precipitation. Several types and designs of rainfall simulator have been proposed to meet a range of research objectives. There had been various field and laboratory studies for observing runoff, soil erosion and infiltration characteristics of rainfall. Most of the researches consisting simulated rainfall have used precipitation at a uniform rate. This is different to natural rainfall, which varies with space and time.

Dorboux et.al., (2001) conducted laboratory experiments on a 2.4 m x 2.4 m soil box exposed to a sequence of four rainfall events using two types roughness conditions and two slope gradients. Surface micro topography was digitized using a laser scanner before and after each rainfall event. Analysis of the runoff triggering showed that a slight change of micro topographic structure had a significant effect on the initiation of runoff.

Thomas et. al., (2000) determined T_C for 78 urban and rural watersheds in Maryland and a regression equation for Tc was developed according to the watershed characteristics. The regression equation was based on the amount of area covered with lakes, ponds, and forests; the amount of area covered with non-infiltrating areas; the channel length and slope. The equation was relevant for determining T_C for urban and rural areas in Maryland. The values of T_C calculated at Maryland gauging stations were compared with empirical equations in the literature such as the Kirpich, and the Soil Conservation Service (SCS) lag equation and with basin lag times determined by the United States Geological Survey (USGS). The values of T_C calculated in this analysis were about five percent greater than the estimates of basin lag time, which is compatible with the USGS definition of lag time. Time of concentration computations from the SCS or Kirpich formula were observed to be lower than the values calculated from the gauging station data.

Merz and Plate (1997) investigated the effects of antecedent soil moisture and its spatial variability on rainfall runoff process for a catchment of small-scale in southwest Germany. Researchers showed that organization in spatial patterns of soil moisture and soil properties might have a significant influence on the catchment runoff. The analysis of different events showed the changing influence of spatial variability on the runoff with changing storm size. Researchers found that for very large and for small events, spatial variability plays a negligible role. A substantial influence is found for medium sized events.

Hotchkiss et. al., (1995) conducted studies to discover the most suitable method for prediction of peak discharge to use on small agriculture watersheds in Nebraska. Accurate peak discharge estimates are needed for the design of highway culverts to ensure economic design and to prevent possible flood damages. Researchers compared seven T_C equations to observed T_C values from 4 watersheds each less that 5 square kilometer in area. The recorded peaks and the historical records were than compared with six peak flow methods. An improved form of Kirpich equation and the U.S. Soil Conservation Service average-velocity equation predicted T_C adequately, based on the data of three storm seasons.

Sheridan (1994) developed hydrograph time parameters for Flatland watersheds of Southeastern United States. Researchers found that the available empirical equations generally under-predicted the observed hydrograph time parameters on 9 coastal plains and Flatwoods watersheds, with standard error ranging from 63 to 132 percent of the observed means. Researchers related the hydrograph time parameters from Flatland study areas to watershed physical characteristic and geomorphic data. Researchers developed an empirical relationship to estimate hydrograph time parameters for Flatland areas.

Akan (1989) presented an explicit formula for determining $T_C$for pervious, plane rectangular catchments. The proposed formula takes into account the length, slope and surface roughness, and the porosity and hydraulic conductivity of the soil are also considered. The proposed formula also takes into account the rate of rainfall, and the antecedent moisture content of the soil.

Huggins (1982) showed that the Kirpich formula correlate poorly with T_C of gauged runoff measurements made from small watersheds of area less than 5 km^2. This discrepancy is attributed to the process of runoff generation mechanism in small watersheds which is dominated by overland flow process rather than dominated by channel flow. Huggins (1982) proposed a formula for T_C considering overland flow and channel flow processes, though the former process may be dominant. It is expressed as:

$$T_C = 0.01952\ L_C^{0.77} S_C^{-0.385} + [2Ln/\sqrt{S}]^{0.467}$$

Singh (1976) derived expressions for T_C from the kinematic wave theory. Researchers considered two types of geometric arrangement in the derivations i.e. the rectangular plane section and the converging section. It was shown that Kirpich equation was a special case of generalized expressions. Researchers also found that the precipitation duration has a significant influence on T_C.

Chapter 3 METHODOLOGY

3.1 LABORATORY SETUP OF ADVANCED HYDROLOGIC SYSTEM

The instrument on which experiments were performed is the Advanced Hydrologic System (AHS; Figure 3.1). The Advanced hydrologic System could be used to demonstrate some of the major physical processes found in hydrology and fluvial geomorphology, such as rainfall hydrographs for catchment areas of varying permeability; the formation of river features and effects of sediment transport; the abstraction of groundwater by wells, both with and without surface recharge from rainfall. Realistic results can be obtained from this instrument, which can be conveniently located in a laboratory.

3.2 INVESTIGATION CAPABILITIES

1. Rainfall-Runoff relationships
2. Generation of overland flow
3. Initiation and characteristics of bed load motion
4. Effect of changing stream power on channel morphology
5. Effect of base level change
6. Scour in open channel flow
7. Water abstraction from a well in a confined aquifer
8. Water abstraction from a well in an unconfined aquifer
9. Water abstraction from a number of neighbouring wells

3.3 FEATURES OF THE INSTRUMENT

1. Novel outlet tank design for water flow and sediment flow measurement
2. Sand tank made of stainless steel
3. Slope adjustments using dual jacks
4. Adjustable spray nozzle height
5. Use of fine grained sand allows detailed feature development

6. Single grade of sand for all defined demonstrations, no need to change the sand

7. Control and measurement of inlet flows

8. Flexible configurations allows a wide range of simulations

Figure 3.1 Advanced Hydrologic System

3.4 DESCRIPTION OF EXPERIMENTAL SETUP

The instrument comprises of a stainless steel made sand tank of dimension 2m x 1m. Rainfall can be sprayed to the sand tank from the nozzles located above the sand tank (simulating rainfall). Water can also be applied in the form of a river flow from an inlet tank simulating a river flow. In this study, the valve of river flow was kept closed and only the spray nozzles were used for simulating rainfall. The output of the water enters into the stilling basin in the form of runoff located at the end of the sand tank. The runoff that reaches the stilling basin passes over the rectangular weir to give the height of runoff over the weir. The runoff then enters a large plastic sump located under the sand tank and the water is re-circulated again in the form of rainfall from the spray nozzles. Twenty tapping points configured in a cruciform pattern, and displayed on the manometer are arranged to measure the ground water table levels (Phreatic surface).

The apparatus consists of eight spray nozzles made up of stainless steel and mounted on a gantry above the sand tank (Figure 3.5). An on/off valve is provided with each spray nozzle through which a wide range of moving rainfall patterns can be simulated. These spray nozzles are positioned in such a way to give uniform distribution of rainfall throughout the sand tank. The apparatus also consists of height adjustment arrangements which can be used to observe the uniformity of rainfall at various different heights (Figure 3.10).

A ½ hp motor is used for generating rainfall (Figure 3.11). The input of water can be adjusted by two variable area flow meters (Figure 3.12). Out of the two flow meters, one is provided for adjusting the rainfall, while the other is provided for adjusting the river flow. The two flow meters have different ranges (0 to 5 litre/min and 0 to 3 litre/min), further improving the flexibility of the overall system.

At the end of the sand tank, the outlet tank is located. The outlet tank comprises of a water stilling basin. The stilling basin consists of a sand trap to trap the sediments and a depth sensor to measure the height over the weir. The measurement of flow is done by observing the height of runoff over the outlet weir. The sand trap allows us to measure the quantity of sediment collected in the basin over a period of time (Figure 3.8). Sand of particle diameter of size 0.5 mm to 1.0 mm is required for filling the sand tank. In this instrument, there is a slope adjustment device for adjusting the slope in the range of 0% to 5% (Figure 3.9). Similar arrangement for rainfall flow rate with different intensity reaches the pipe line which is arranged above the sand tank and through the spray nozzle artificial rainfall is spread over the catchment area of sand tank that is 2m x 1m. During rainfall water flows over the surface of sand to reach the outlet and this runoff water flows through the collecting tank filled with rectangular weir to measure the runoff water passing over it. The Depth sensor is placed in the collecting tank to give the height over weir.

3.5 EXPERIMENTAL DETAILS

All the experiments described here were conducted in the laboratory of Department of Hydrology, IIT Roorkee. The experiments were carried out in a sand tank of uniform rectangular cross section 1 meter wide and 2 meter long. A 350kg of fine sand with Manning’s coefficient (n=0.02) was used to fill the sand tank. The slope of the plane was varied between 0.5% to 3% and the flow rate was varied between 1.5 litre/min to 3 litre/min to generate artificial rainfall through eight nozzles over the catchment area.

3.6 RAINFALL TEST PROCEDURE

As the experiments were carried out in laboratory, so there was no loss of rainfall water due to the effects of wind and due to other environmental factors. The experimental procedure was as follows:

1. Antecedent moisture content of the soil profile was measured by using soil moisture sensors (Decagon Device, USA). A set of three sensors were used. Two of them were placed at the edges and one was placed at the centre (Figure 3.4). The values given by these three sensors were than averaged out to give the antecedent moisture of the soil profile.
2. The slope of the plot was varied between 0.5 to 3% by using the slope adjustment device (Figure 3.9).
3. Intensity of rainfall was varied by varying the inflow rate and dividing it by the area of the plot.
4. Stop watch was used to record the time when runoff appears on the runoff collection system as the time of beginning.
5. Runoff measurements were taken at an interval of 10 seconds using Odyssey water level recorder (Figure 3.6).
6. The runoff rate was monitored continuously.
7. The instrument was switched off after the runoff peaked and the time was recorded as the time to peak.
8. The runoff measurements were continued until runoff ceased.

A typical hydrograph describing the overland flow time parameters is shown in figure 3.2 below. A rainfall test will begin at time zero when the rainfall simulator was turned ON. Initially there was no flow period at the outlet. Time of beginning was recorded when the first flow was observed at the outlet. As the flow plateaued and fluctuated within 5% of the flow rate, the rate was considered as the peak, which determined the time to peak. Because T_C should involve only hydraulic travel time, the initial loss process (initial abstraction) was not considered as part of T_C. Therefore, T_C in the rainfall test is determined as the time to peak minus the time of beginning of runoff.

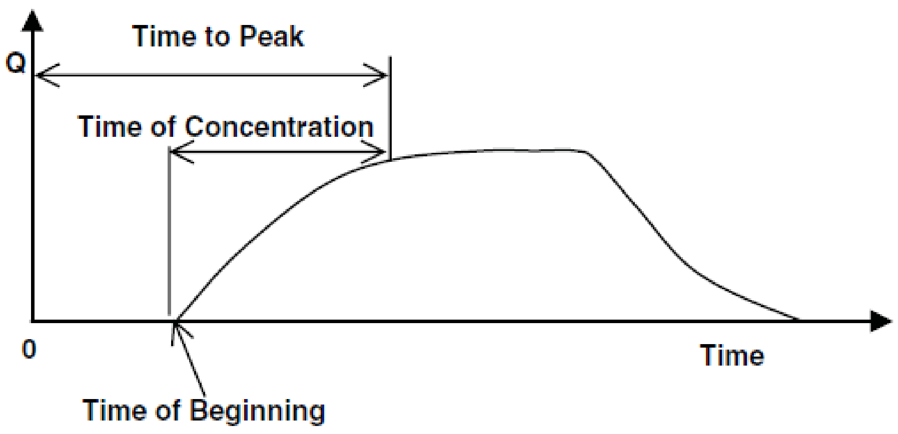

Figure 3.2 A typical hydrograph showing time parameters

The following methodology was adopted while conducting this study:

1. Estimation of T_C subjected to varying slopes using Kirpich equation.
2. Estimation of T_C subjected to varying slopes using rainfall simulator.
3. Development of relationship of T_C as computed above, versus other independent variables on the basis of a number of experiments conducted using the rainfall simulator.
4. Comparison of the improved T_C expression developed from rainfall simulator with the Kirpich equation and various other existing T_C equations.

Figure 3.3 General view of laboratory set up of the instrument

Figure 3.4 Soil moisture sensors for measuring antecedent soil moisture content

Figure 3.5 Eight spray nozzles for generating rainfall over the catchment area

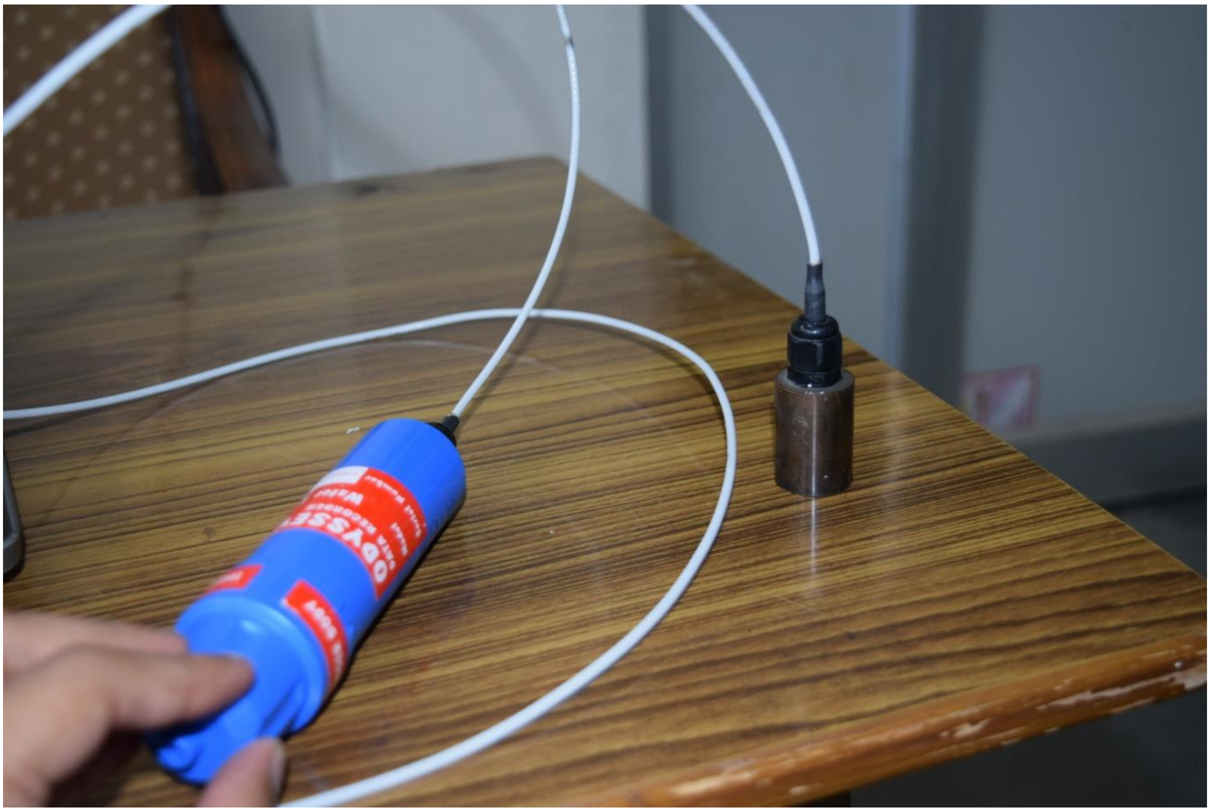

Figure 3.6 Odyssey water level recorder for measuring depth of runoff

Figure 3.7 Tank filled with fine sand of size 0.5 mm to 1 mm

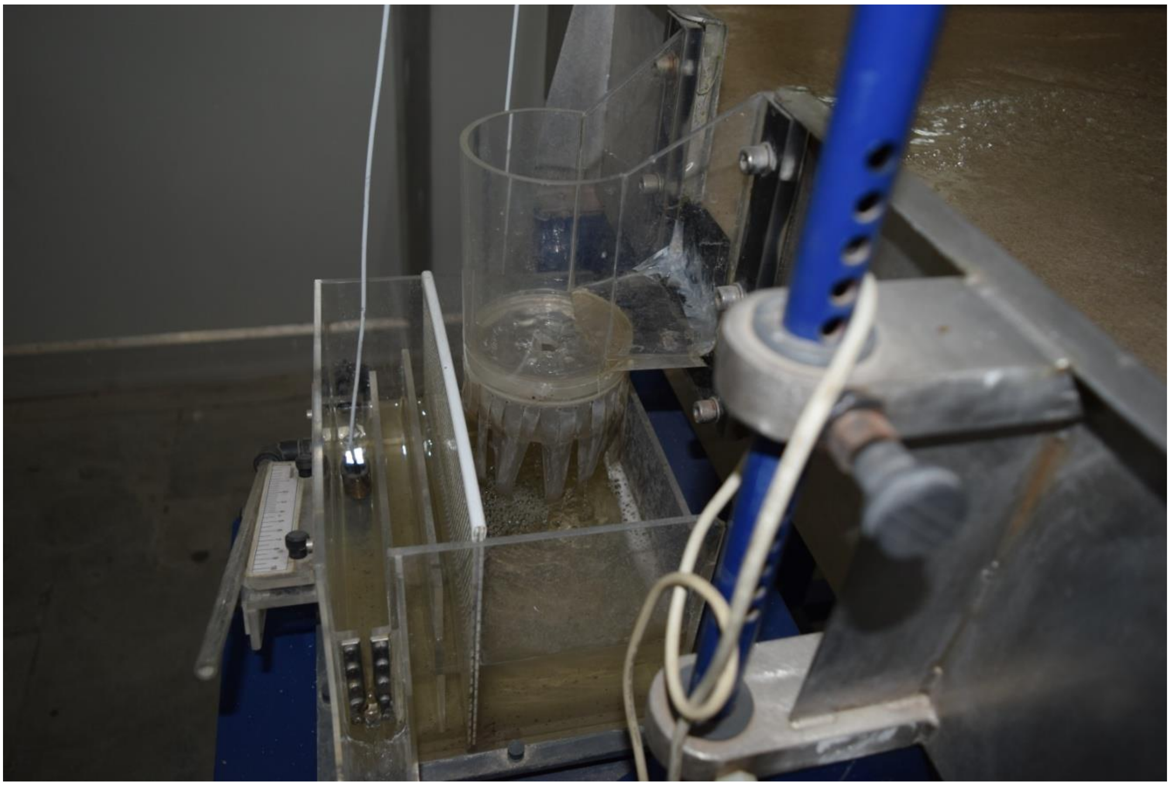

Figure 3.8 Runoff water measuring device with rectangular weir

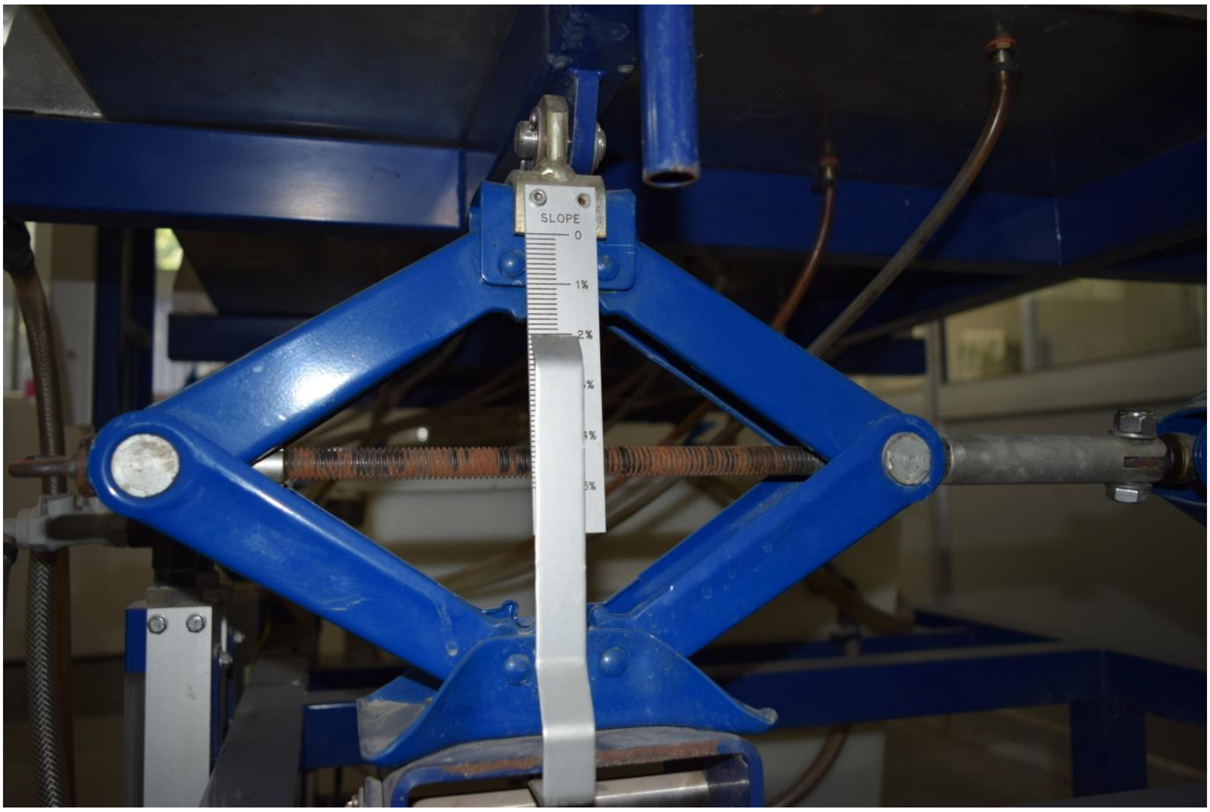

Figure 3.9 Slope adjustment device

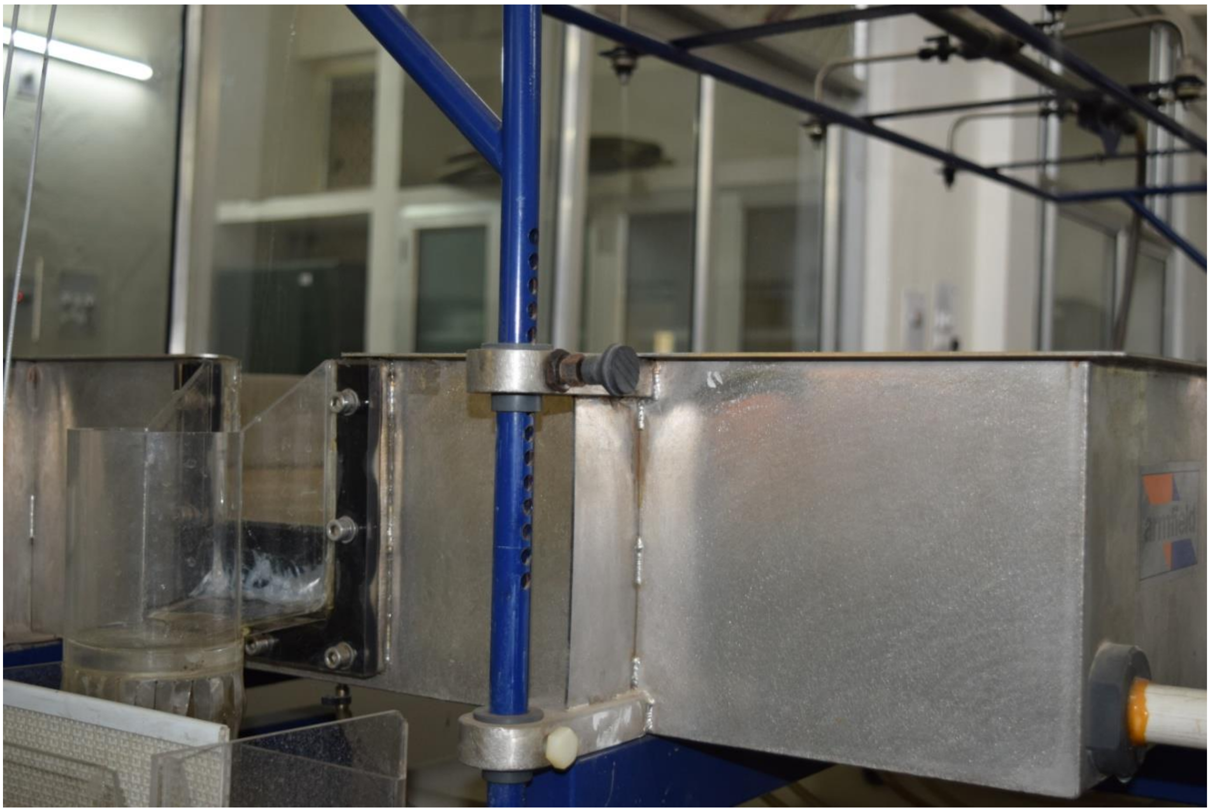
Figure 3.10 Height adjustments for spray nozzles

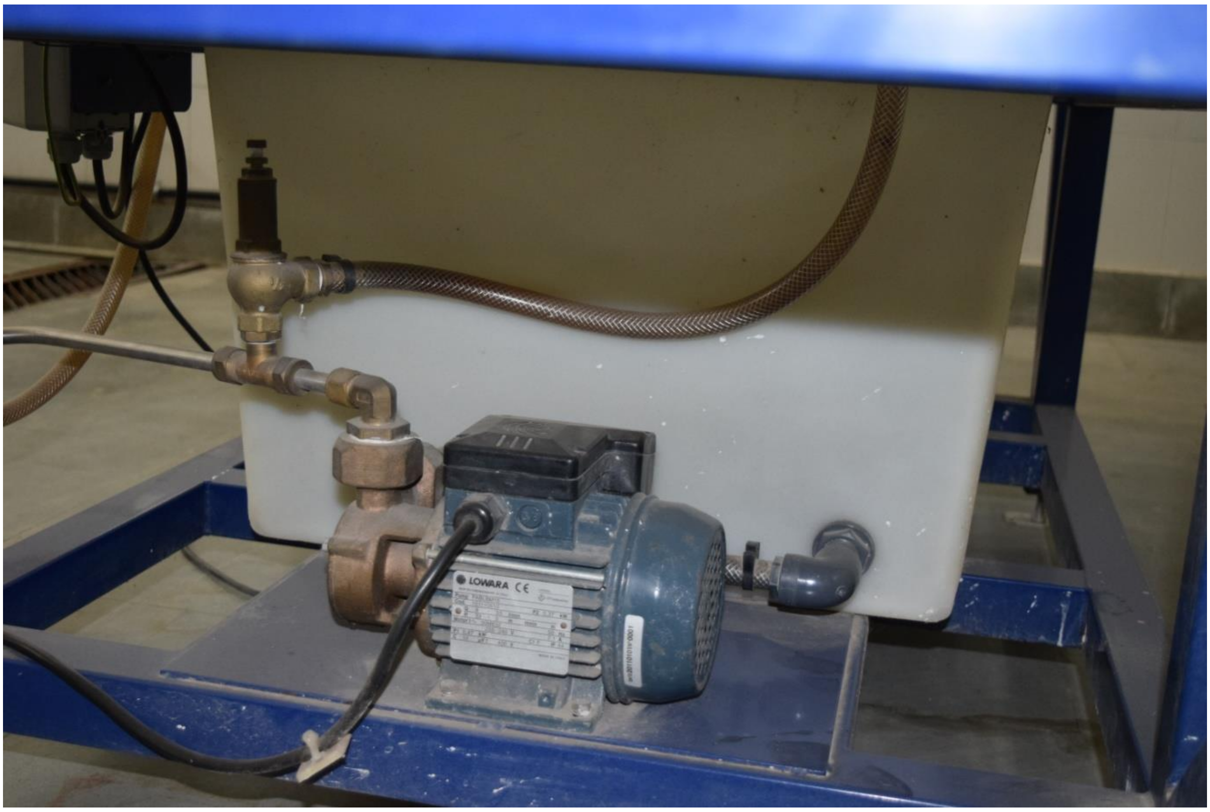

Figure 3.11 Half hp motor for artificial rainfall

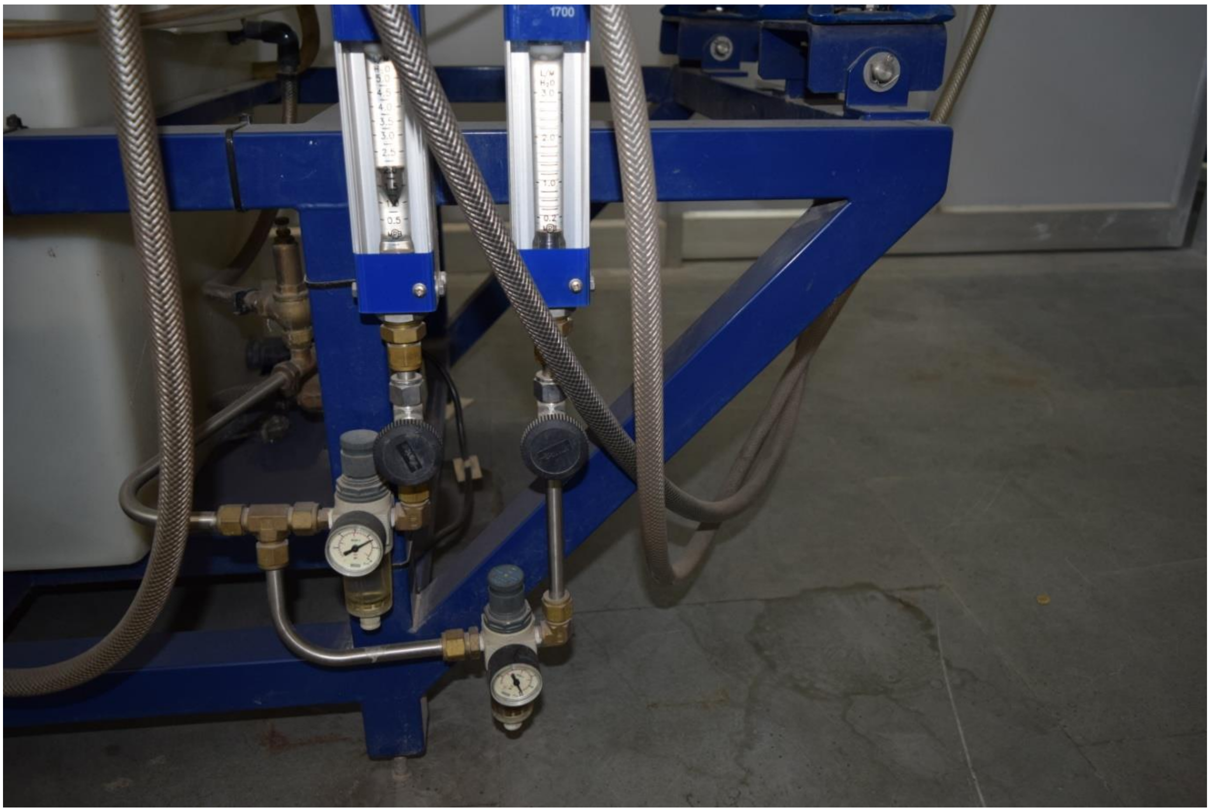

Figure 3.12 Flow meter

Chapter 4 RESULTS AND DISCUSSION

4.1 PRELIMINARY DATA ANALYSIS

A total of 35 experiments were performed on the Advanced Hydrologic System (Rainfall Simulator) to measure the overland flow at different slopes, intensities and antecedent moisture content of soil. Slopes were varied between 0.5% to 3%. Intensities were varied between 45mm/hr to 90mm/hr and moisture content of soil was varied between 8% to 28%. A sand tank of plot area 2m x 1m was used and 350kg of fine sand was placed inside the tank to prepare the bed. Each rainfall test was run for a period of 15 to 30 minutes. Before starting the experiment, the moisture content of the soil was measured using soil moisture sensors.

Figure 4.1 to 4.4 shows some of the stage hydrographs observed in this study. A stage hydrograph is a graph that shows how the water level at a particular location changes with time. A stage hydrograph must be referenced to a particular datum. From Figure 4.1 to 4.4, it can be seen that after the start of the rainfall on the catchment, the water flow rate at the outlet increases rapidly with time, this portion of hydrograph is known as the rising limb. However at a certain time the water flow rate at the outlet equals the rainfall intensity, this time is known as time to peak (T_P). After the occurrence of time to peak, the rainfall flow rate almost becomes constant with time. However, minor fluctuations are still observed, these may be due to variety of reason including actual flow phenomenon. When the rainfall is stopped, initially the water flow rate at the catchment outlet starts reducing at a very rapid rate till a time is reached when the flow rate starts reducing at a very slow rate till a no flow condition is observed at the outlet. This is known as the falling limb of hydrograph. The enlargement of falling limb with time may be due to the fact that after stopping the rainfall intensity, some amount of water is still stored in the overhead pipe. This volume of water is then released subsequently from the nozzle due to the gravity.

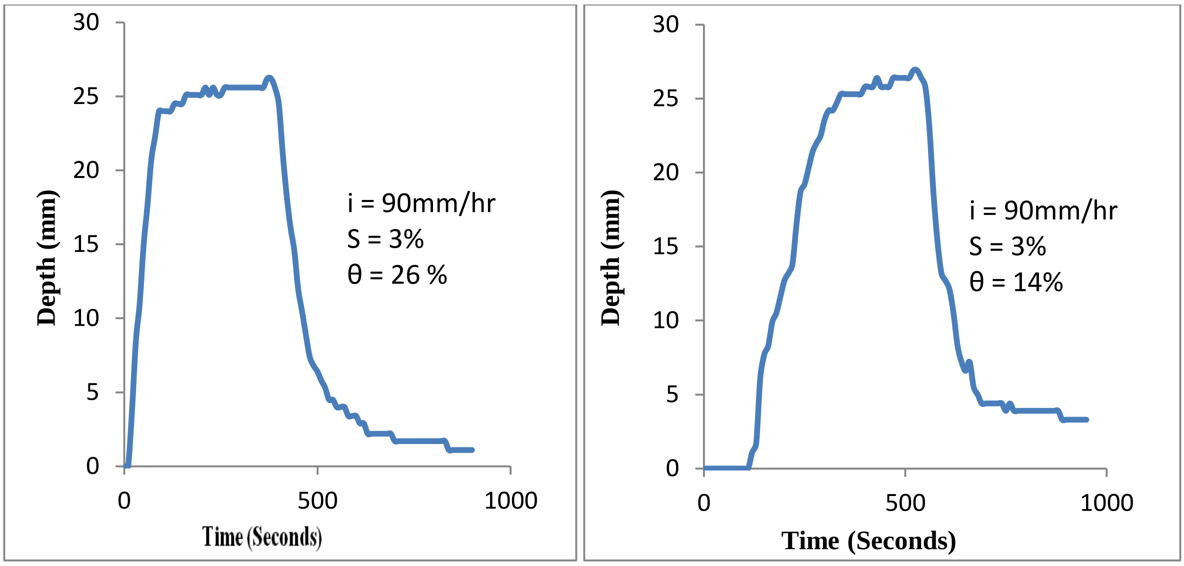

Figure 4.1 Observed hydrographs for 90 mm/hr rainfall

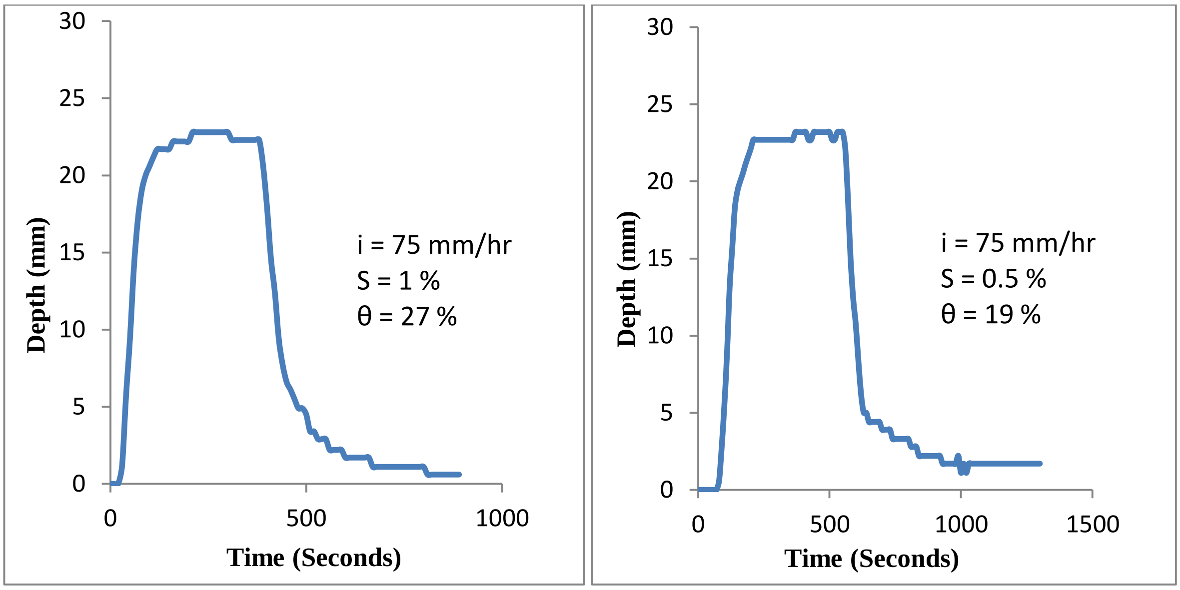

Figure 4.2 Observed hydrographs for 75 mm/hr rainfall

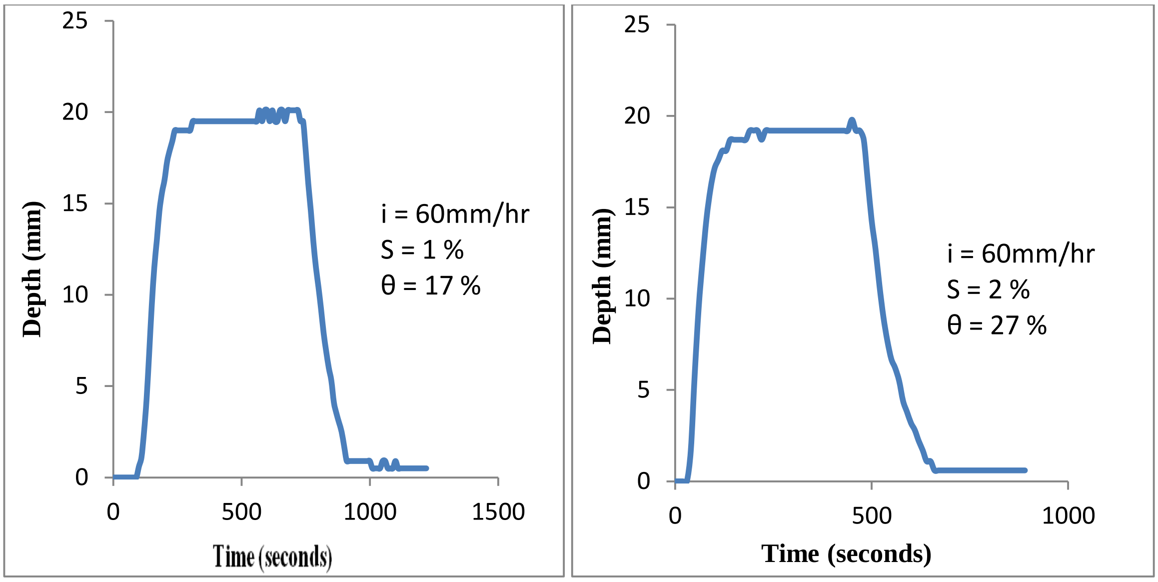

Figure 4.3 Observed hydrographs for 60 mm/hr rainfall

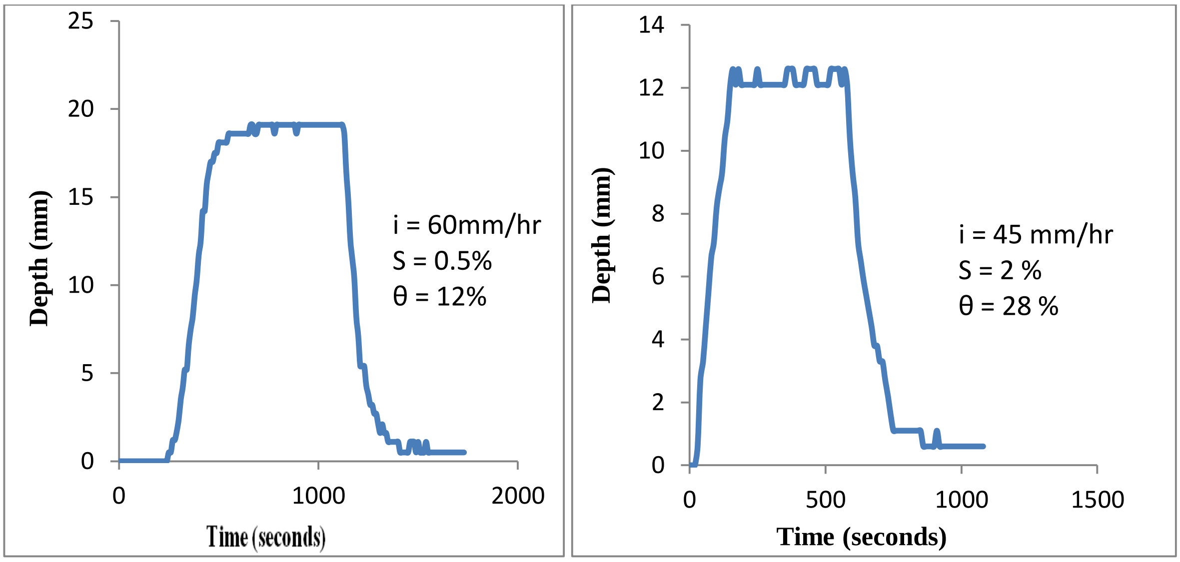

Figure 4.4 Observed hydrographs for 60 and 45 mm/hr rainfall

Table 4.1 Overland flow times for 45 mm/hr rainfall

Slope (%)	Antecedent soil moisture (%)	Time of Beginning (mins)	Time to Peak (mins)	Time of concentration (mins)
0.5	23	1.5	6.16	4.66
0.5	28	0.5	3.66	3.16
1	26	1	4	3
1	28	0.5	2.83	2.33
2	19	2.16	5.83	3.67
2	28	0.5	2.66	2.16
3	13	3.66	8	4.34
3	25	0.66	3.5	2.84
3	28	0.33	2.33	2

Table 4.2 Overland flow times for 60 mm/hr rainfall

Slope (%)	Antecedent soil moisture (%)	Time of Beginning (mins)	Time to Peak (mins)	Time of concentration (mins)
0.5	12	4.16	8.33	4.17
0.5	25	0.83	2.83	2
1	17	1.66	4	2.34
1	24	0.83	2.83	2
2	22	1.16	3.33	2.17
2	27	0.66	2.33	1.67
3	18	1.16	3.5	2.33
3	26	0.5	2	1.5

Table 4.3 Overland flow times for 75 mm/hr rainfall

Slope (%)	Antecedent soil moisture (%)	Time of Beginning (mins)	Time to Peak (mins)	Time of concentration (mins)
0.5	19	1.33	3.5	2.17
0.5	26	0.66	2.33	1.67
1	12	3.16	7.16	4
1	20	1	3.16	2.16
1	27	0.5	2	1.5
2	19	1	3.16	2.16
2	26	0.5	2	1.5
3	18	0.83	2.83	2
3	26	0.33	1.66	1.33

Table 4.4 Overland flow times for 90 mm/hr rainfall

Slope (%)	Antecedent soil moisture (%)	Time of Beginning (mins)	Time to Peak (mins)	Time of concentration (mins)
0.5	15	2	5.83	3.83
0.5	26	0.5	2.16	1.66
1	19	0.66	2.83	2.17
1	27	0.5	2	1.5
2	23	0.66	2.33	1.67
2	27	0.33	1.66	1.33
3	8	6.5	13.83	7.33
3	14	2	5.66	3.66
3	26	0.33	1.5	1.17

4.1.1 EFFECT OF ANTECEDENT MOISTURE ON T_C

Initially when the rainfall simulator was switched on, there was some time lag observed in the beginning of runoff. This time lag was more in the case of soil with low moisture content and less in the case of soil with high moisture content (Figure 4.1 to 4.4). The observed time lag can be attributed to the fact that initially water infiltrates through the soil before the runoff begins. The peak of runoff was reached earlier in the case of high moisture content soil whereas the soil with low moisture content took more time to reach its peak. This may be due to the initial abstraction of soil and simultaneous beginning of runoff before all the voids of soil are filled completely, which was also observed by Hansen et. al., (2000). Hence, the shape of the resulting hydrograph was influenced by the antecedent moisture content, which was also observed by Asch et. al., (2001) and Meyles et. al., (2003) . The effect of moisture content can be seen from Table 4.1 and 4.4. At 45mm/hr rainfall intensity, 0.5% slope and 28% moisture content, T_C was observed as 3.16 minutes whereas at 90mm/hr rainfall intensity, 3% slope and 8% moisture content, T_C was observed as 7.33 minutes. Even though the rainfall intensity and slope was kept lowest in the first case and the rainfall intensity and slope was kept highest in the second case, T_C was higher for the second case which was due to very low moisture content.

4.1.2 EFFECT OF SURFACE SLOPE ON T_C

During the first set of experiments, the rainfall intensity was kept constant at 45mm/hr and slopes were varied at 0.5%, 1%, 2% and 3% with soils of different moisture content. It was found that as the slope was increasing, T_C was decreasing at constant rainfall intensity and almost similar moisture contents. Similar trends were also observed in the case of 60mm/hr, 75mm/hr, and 90mm/hr rainfall intensity. However, the effect of slope on T_C was not as dominant as the effects of antecedent moisture and rainfall intensity. The effect of slope can be seen from Table 4.1. At constant moisture content of 28% and 45mm/hr rainfall intensity, and slopes varying from 0.5%, 1%, 2%, 3%, the T_C values were 3.16, 2.33, 2.16, and 2 minutes, respectively. The higher difference between the T_C values at 0.5% slope and other values of slope may be due to the lesser effect of slope variable on T_C on very flat surfaces.

4.1.3 EFFECT OF RAINFALL INTENSITY ON T_C

In the four sets of experiment, the rainfall intensity was increased from 45mm/hr, 60mm/hr, 75mm/hr to 90mm/hr. It was observed from Table 4.1 to 4.4, that for a given slope and given antecedent moisture, T_C decreases with the increase in rainfall intensity. The effect of rainfall intensity on T_C is more predominant than surface slope. On very low sloped surfaces i.e. surfaces with slopes less than 0.5%, the effect of slope diminishes and the effects of rainfall intensity and antecedent moisture content dominates T_C. The effect of rainfall intensity on T_C can be seen in Table 4.1 to 4.4. At constant slope of 2% and moisture content of 27%, and rainfall intensity varying from 45, 60, 75, 90mm/hr , the T_C values are coming out to be 2.16, 1.67, 1.50, and 1.33 minutes respectively. The higher difference between the values at 45mm/hr and other values of rainfall intensity may be due to lesser uniformity and lesser spreading area of rainfall at 45mm/hr.

4.2 COMPARISION OF DIFFERENT TIME PARAMETERS

4.2.1 TIME OF BEGINNING (T_b)

Time of beginning of runoff was found to be more dependent on antecedent moisture content rather than the surface slope and rainfall intensity. From Table 4.4 it can be seen that at constant slope of 3% and rainfall intensity 90mm/hr, and varying moisture content 8%, 14%, and 26%, the T_b values are coming out to be 6.5, 2 and 0.33 minutes respectively. As it can be seen in the Figure 4.5, a decreasing trend and a good correlation of T_b is observed with the antecedent soil moisture. In contrast to it, a relationship of T_b is missing with the rainfall intensity (Figure 4.6). Similarly, a relation of T_b with surface slope is also missing (Figure 4.7). Also, the influence of time of beginning (T_b) on T_C was found to be more than the time to peak (T_P).

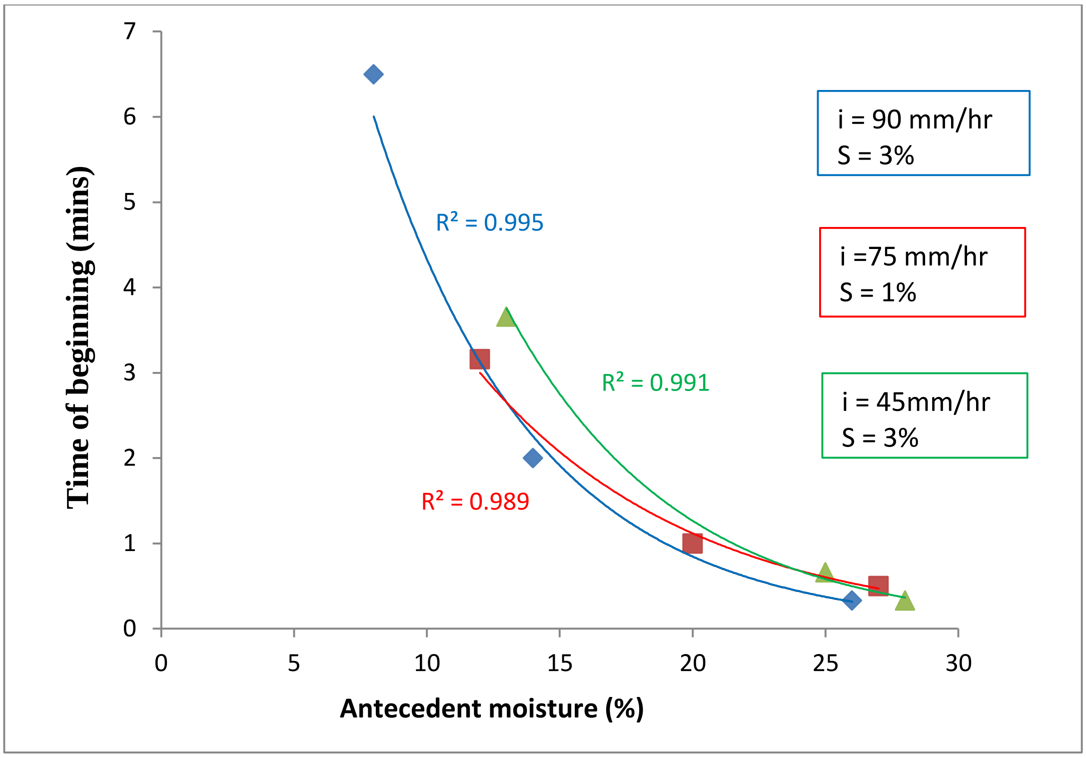

Figure 4.5 Comparison of time of beginning with antecedent moisture

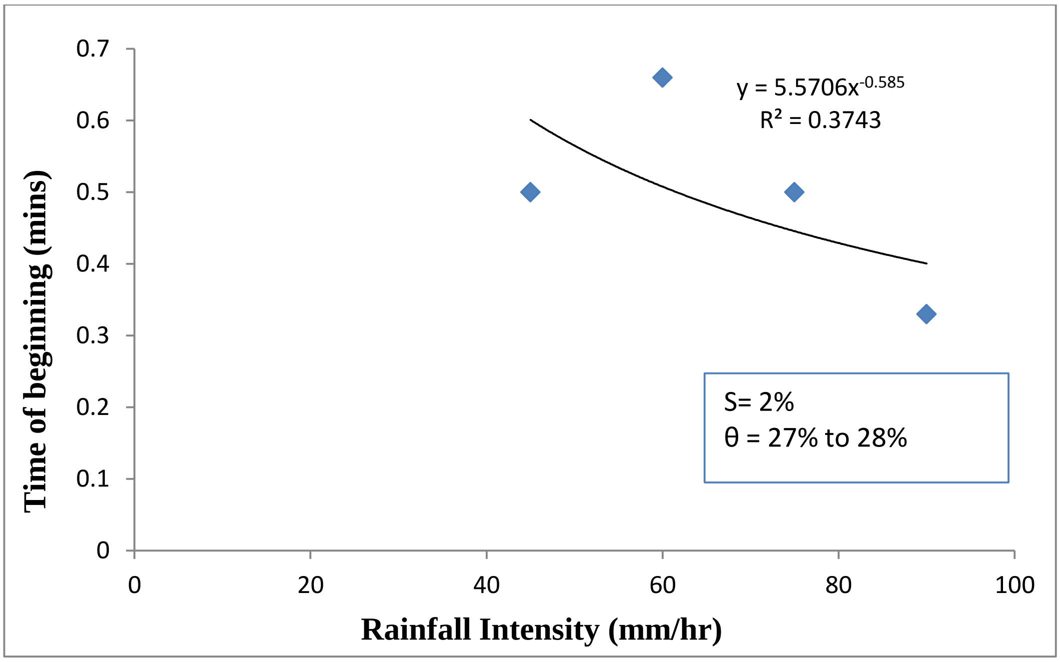

Figure 4.6 Comparison of time of beginning with rainfall intensity

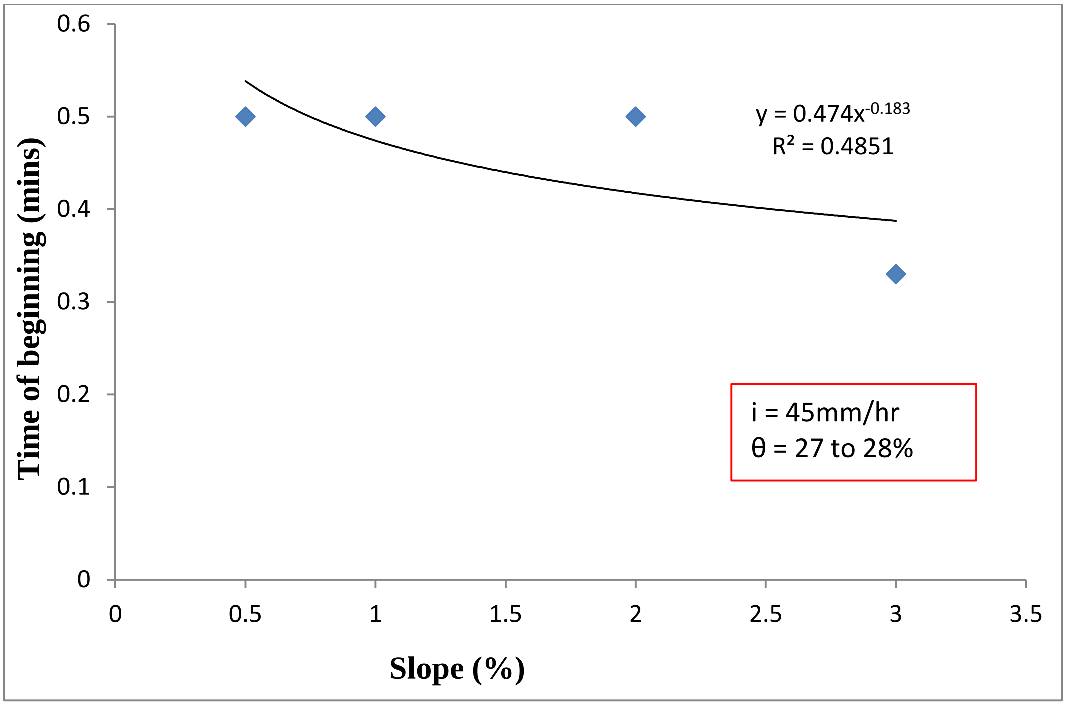

Figure 4.7 Comparison of time of beginning with surface slope

4.2.2 TIME TO PEAK (T_P)

The effect of time to peak (T_P) on the value of T_C was found to be less influential as compared to T_b. This may be due to the smaller length of plot used in this study. Due to the smaller length of the plot, the values T_P were coming less as compared to the plot areas with larger length. Since T_C involves only the hydraulic time of travel, T_b was influencing the T_C values in the case of soils with low moisture content. A decreasing trend of T_P was observed with rainfall intensity, surface slope and antecedent moisture condition (Figure 4.8 to 4.10). As it can be seen in the table 4.3, at constant slope of 1%, and rainfall intensity 75mm/hr, and varying moisture content 12%, 20%, and 27%, the T_P values are coming out to be 7.16, 3.16 and 2 minutes respectively (Figure 4.8). From table 4.1 to 4.4, for a constant antecedent moisture condition, as the intensity increases from 45mm/hr to 90mm/hr, T_P decreases (Figure 4.9). Similarly, for a constant antecedent moisture condition, as the slope increases from 0.5% to 3%, the time to peak decreases (Figure 4.10).

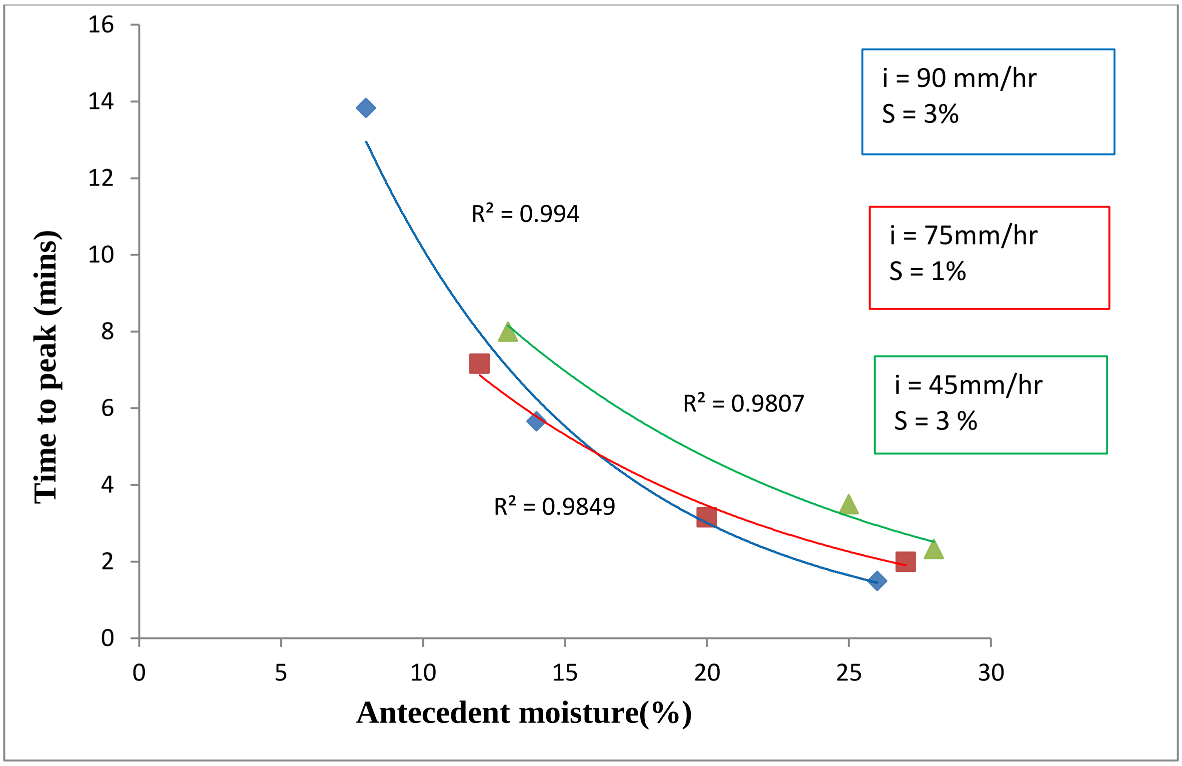

Figure 4.8 Comparison of time to peak with antecedent moisture

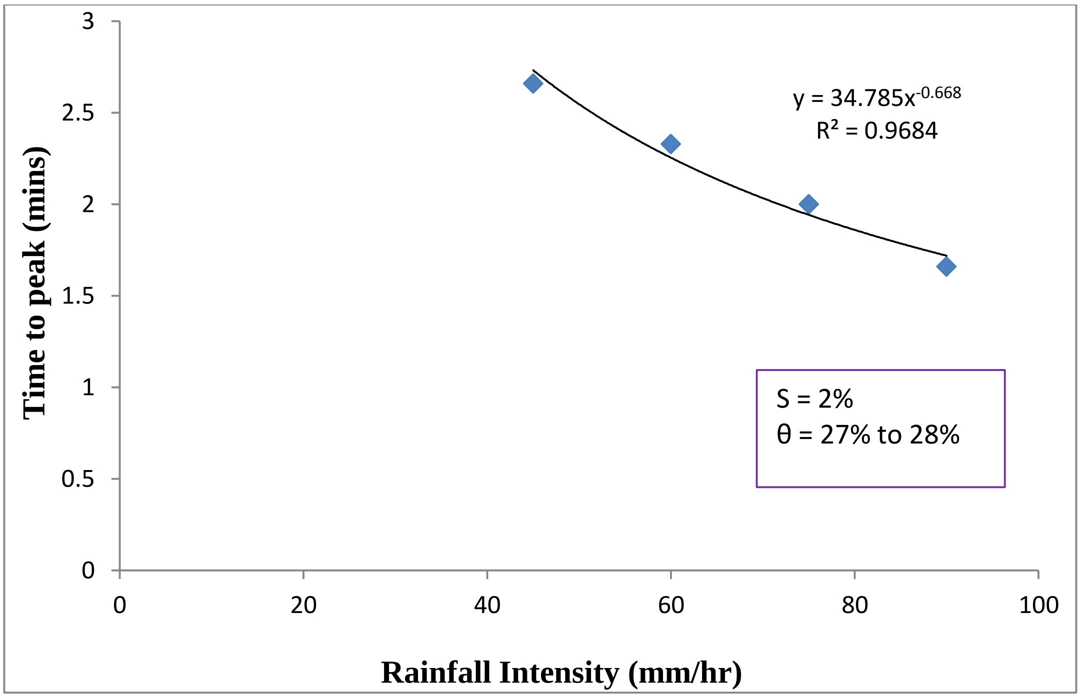

Figure 4.9 Comparison of time to peak with rainfall intensity

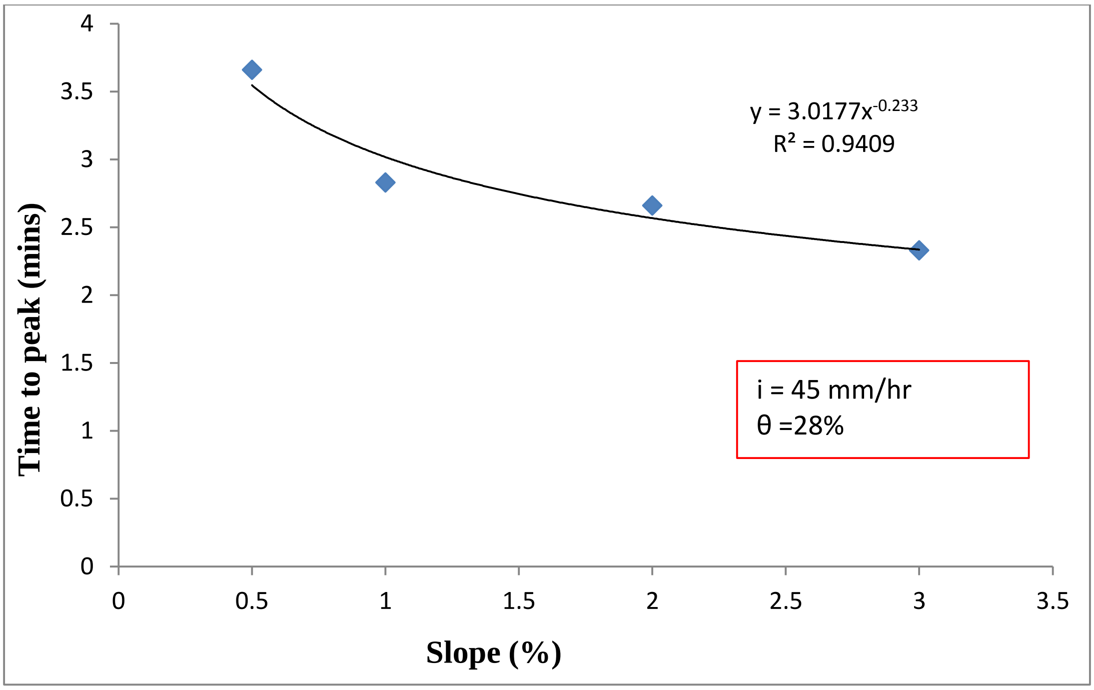

Figure 4.10 Comparison of time to peak with surface slope

4.2.3 TIME OF CONCENTRATION (T_C)

The time of concentration was found to be more dependent on antecedent moisture content rather than rainfall intensity and surface slope. For similar moisture content, irrespective of intensity and slope, the variations in T_C values were small. However, larger variations in T_C values were observed in the case of soils with larger difference in soil moisture. A decreasing trend of T_C was observed with rainfall intensity, surface slope and antecedent soil moisture (Figure 4.11 to 4.13). As it can be seen from Table 4.3, at constant slope of 1% and rainfall intensity 75 mm/hr, and varying moisture content 12%, 20%, and 27%, the T_C values are coming out to be 4, 2.16 and 1.5 minutes, respectively (Figure 4.11). From Table 4.1 to 4.4, for a constant antecedent moisture condition, as the intensity increases from 45mm/hr to 90mm/hr, T_C decreases (Figure 4.12). Similarly, for a constant antecedent moisture condition, as the slope increases from 0.5% to 3%, T_C decreases (Figure 4.13).

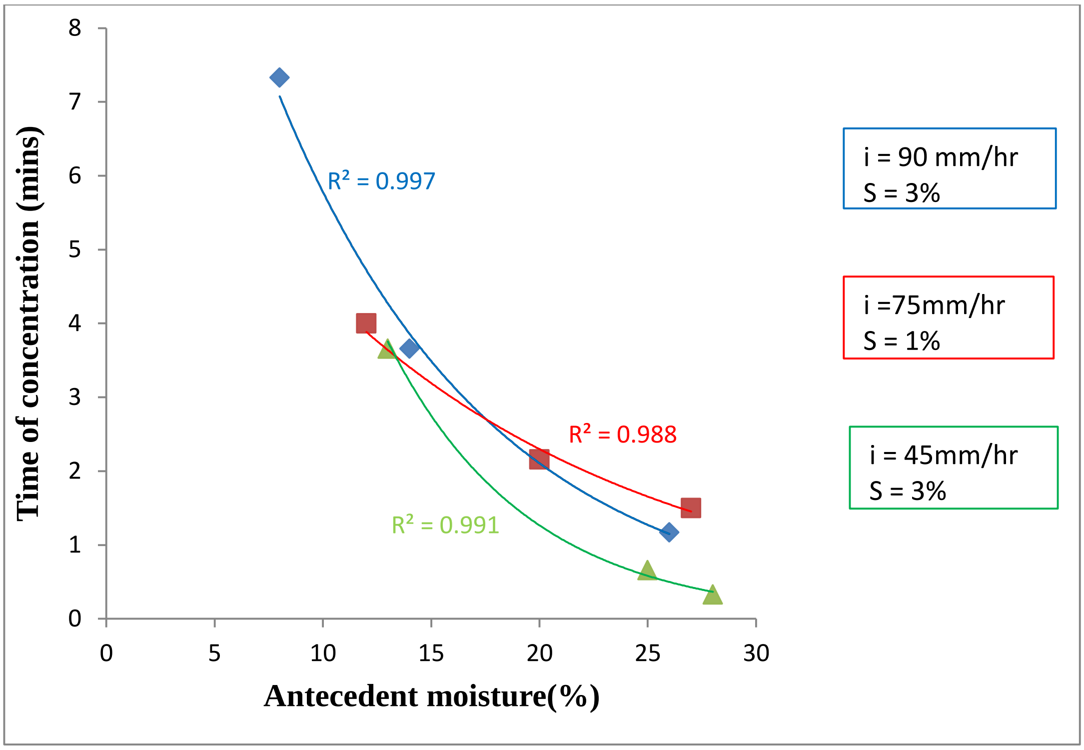

Figure 4.11 Comparison of time of concentration with antecedent moisture

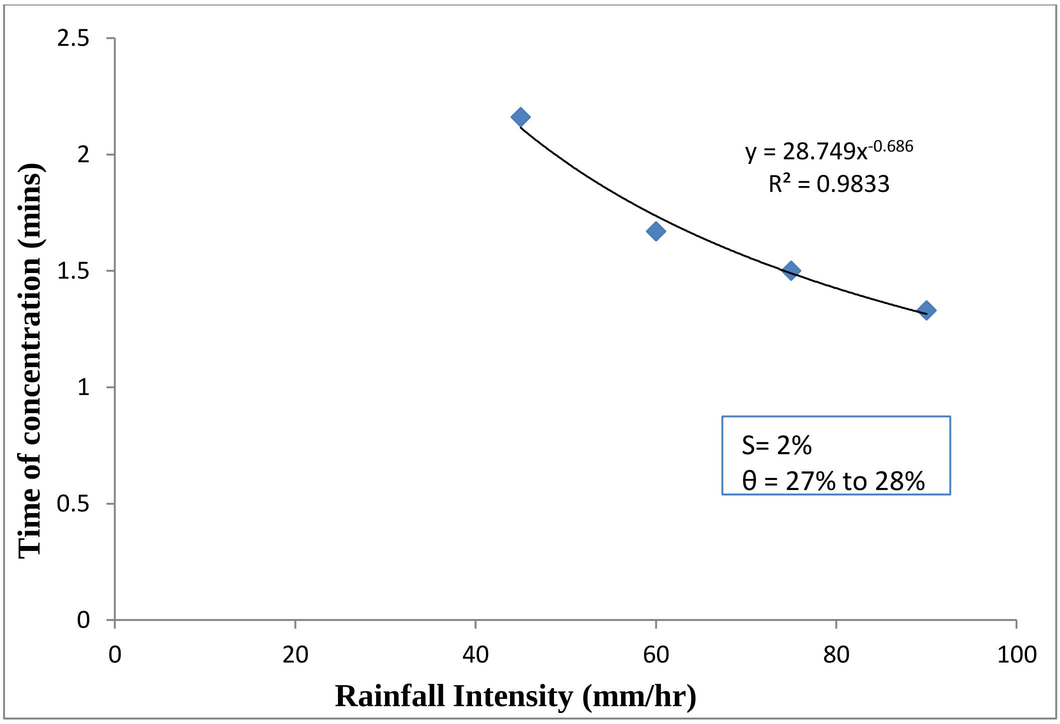

Figure 4.12 Comparison of time of concentration with rainfall intensity

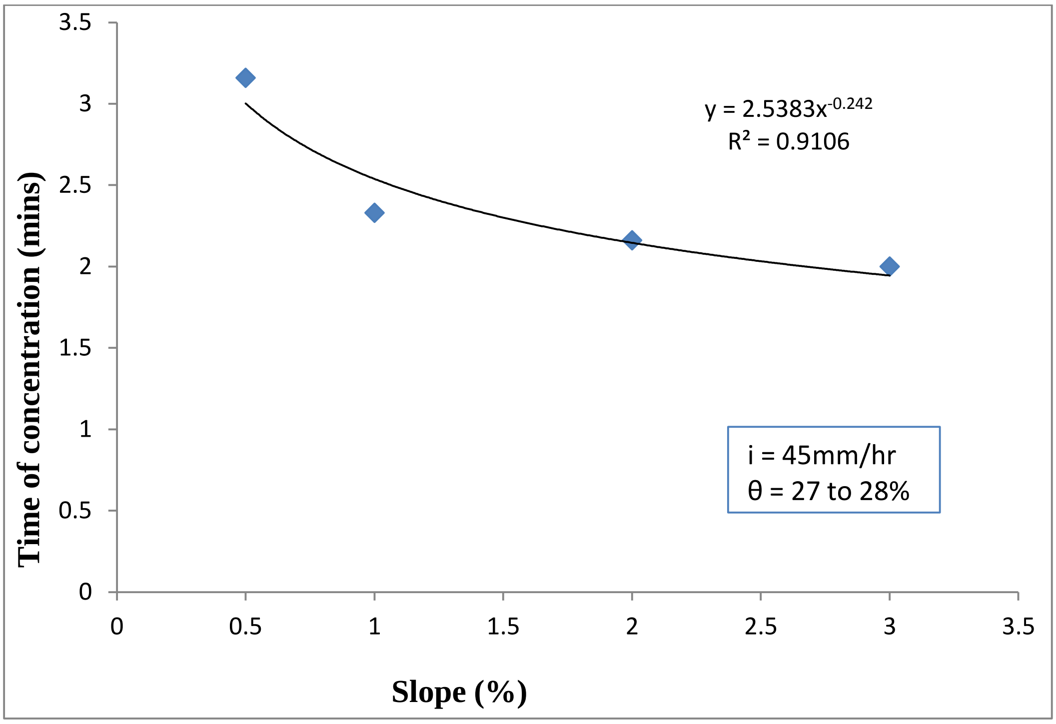

Figure 4.13 Comparison of time of concentration with surface slope

4.3 REGRESSION RESULTS

A general regression equation can be represented as

$$T_C = KL^a n^b \theta^{-x} S^{-y} i^{-z}$$

where, T_C = Time of concentration in minutes; L = Overland flow length in metres; n = Manning's roughness coefficient; θ = Antecedent moisture content in m^3/ m^3; S = Surface slope in m/m; i = Rainfall intensity in mm/hr; K = Constant; a, b, x, y and z = exponents

This equation exhibits a linear relationship for the logarithms of the variables involved. Hence, stepwise regression analysis was performed using the Minitab Software to get the final regressed equation for T_b, T_P and T_C, respectively. Since the length of plot was not varied and experiments were performed only on single surface i.e. fine sand, therefore the exponents 'a' and 'b' has been assumed to be 0.50 and 0.52 respectively as per Papadakis and Kazan (1987) who has given the most comprehensive model to predict T_C summarized from more than 10 models.

Table 4.5 Regression Analysis Summary

	N	R^2	K	x (for θ)	y (for S)	z (for i)
T_C	35	0.85	32.04	-1.22 (0.000)	-0.122 (0.009)	-0.810 (0.000)
T_b	35	0.93	1.108	-2.48 (0.000)	-0.200 (0.001)	-0.770 (0.000)
T_P	35	0.93	25.24	-1.627 (0.000)	-0.146 (0.000)	-0.839 (0.000)

Note: p-value is shown in parenthesis

Hence, the final regressed models can be shown as:

$T_C = 32.04L^{0.50}n^{0.52}\theta^{-1.22}S^{-0.122}i^{-0.810}$

The following inferences can be made from the regression analysis:

1. A new parameter antecedent moisture content (θ) was introduced in the equation which is not included in majority of empirical models. Since the 'p-value' for 'θ' was the lowest and the exponents of 'θ' were the highest amongst the other independent variables, therefore 'θ' was found to be the most sensitive and significant variable in the equation.
2. Since the 'p-value' for all the variables were less than 0.05, hence all the variables were sensitive and significant in the equation. Out of these, the 'p-value' of the slope was the highest and the exponent value of the slope was the least, therefore slope was the least significant variable in the equation.
3. The exponent value of antecedent moisture content (θ) was the highest in the equation of T_b, hence it can be inferred that the antecedent moisture content controls the T_b of runoff.

Figure 4.14 to 4.16 shows the comparison between the observed and predicted times for T_C, T_b and T_P respectively as listed in Table 4.1 to 4.4.

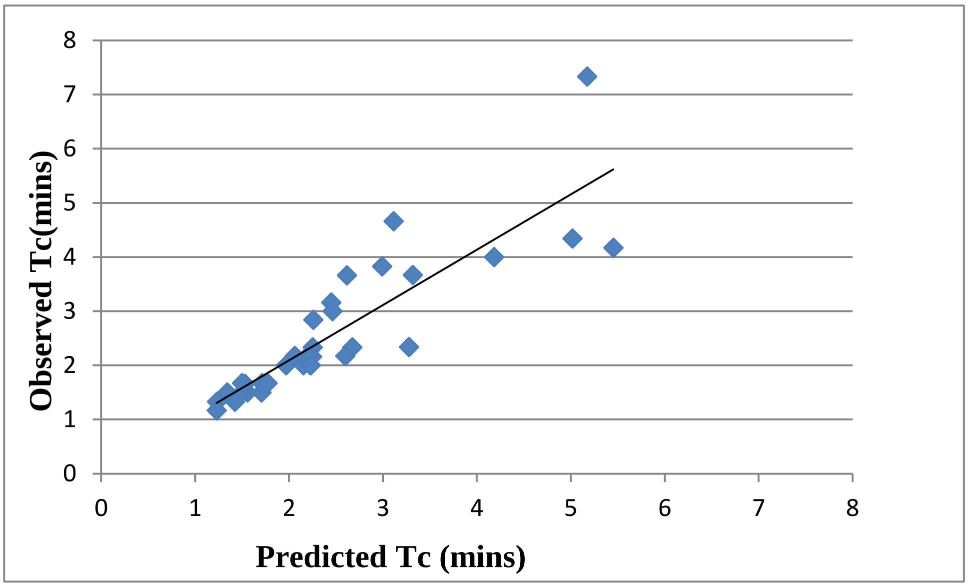

Figure 4.14 Comparison between observed and predicted time of concentration

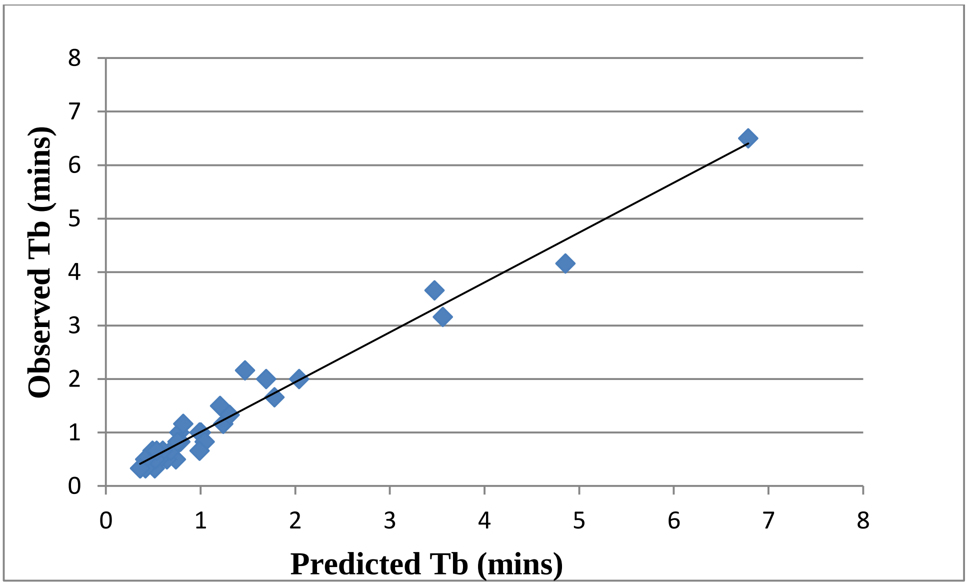

Figure 4.15 Comparison between observed and predicted time of beginning

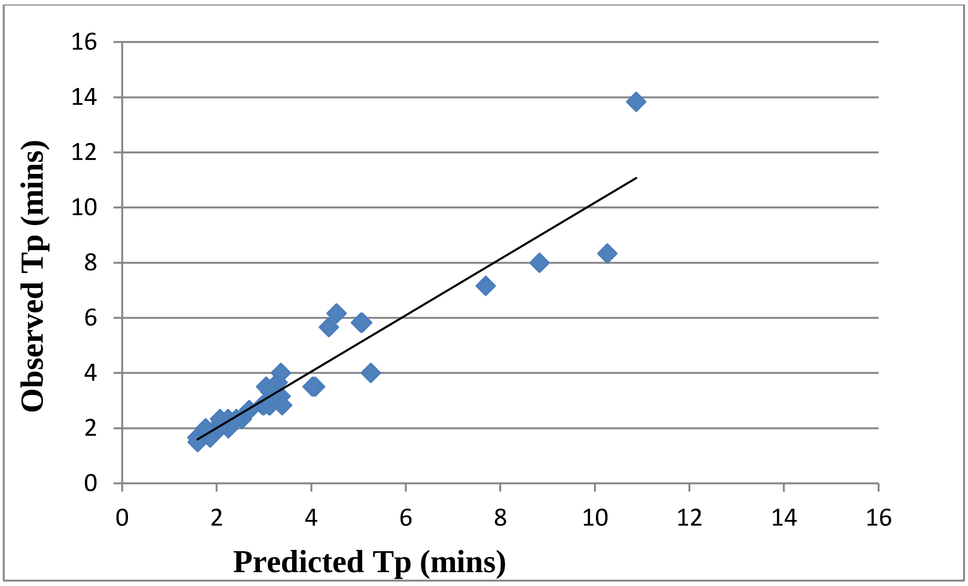

Figure 4.16 Comparison between observed and predicted time to peak

4.4 COMPARISON OF OBSERVED RESULTS WITH DIFFERENT T_C MODELS

The regressed model of T_C predicted in this study is given by

$$T_C = 32.04L^{0.50}n^{0.52}\theta^{-1.22}S^{-0.122}i^{-0.810}$$

This model was compared with different T_C models available in the literature and it was observed that

1. Majority of the empirical models underestimated T_C whereas models such as Mathur and Perumal (2007) and Izzard (1946) overestimated T_C.
2. This variation can be attributed to the fact that different models are developed in different conditions. Also these empirical models are based on different definitions of T_C.
3. The existing models do not contain antecedent soil moisture (θ) parameter which has a significant role to play in determining T_C.
4. Models such as Mathur and Perumal (2007) and Izzard (1946) were showing good results at lower values of antecedent soil moisture content.

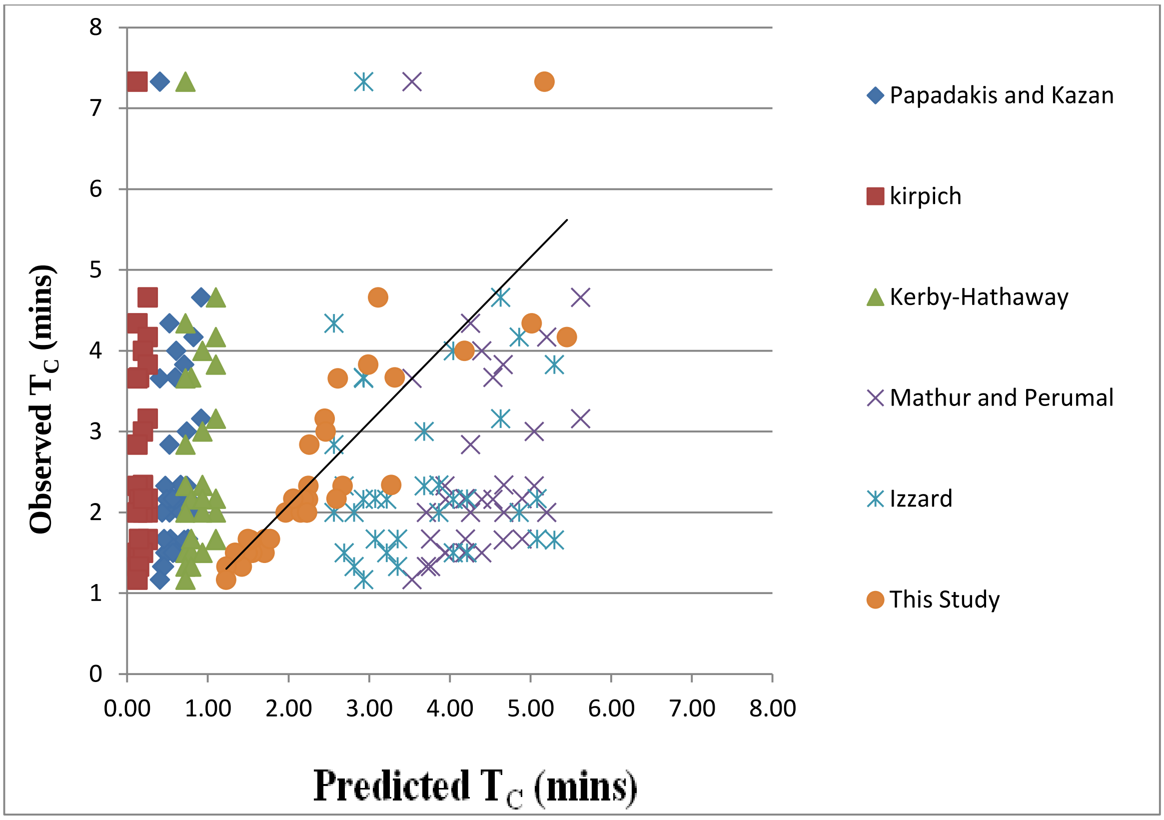

Figure 4.17 Comparison of observed results with different T_C models

4.5 COMPARISON OF OBSERVED RESULTS WITH KIRPICH EQUATION

During this study it was observed that the Kirpich equation under-predicted T_C by 10 times which may be due to the following reasons:

1. The Kirpich equation depends on only two parameters i.e. overland flow length and surface slope whereas other factors such as rainfall intensity, surface roughness and antecedent soil moisture are not included in the equation.
2. Different models are developed in different watersheds which may result in variation in T_C values.
3. Variation in T_C may be attributed to the absence of a clear definition of T_C. Different researchers have defined T_C in various different ways.
4. Kirpich has given higher significance to the slope parameter whereas as per this study the slope was the least significant parameter.

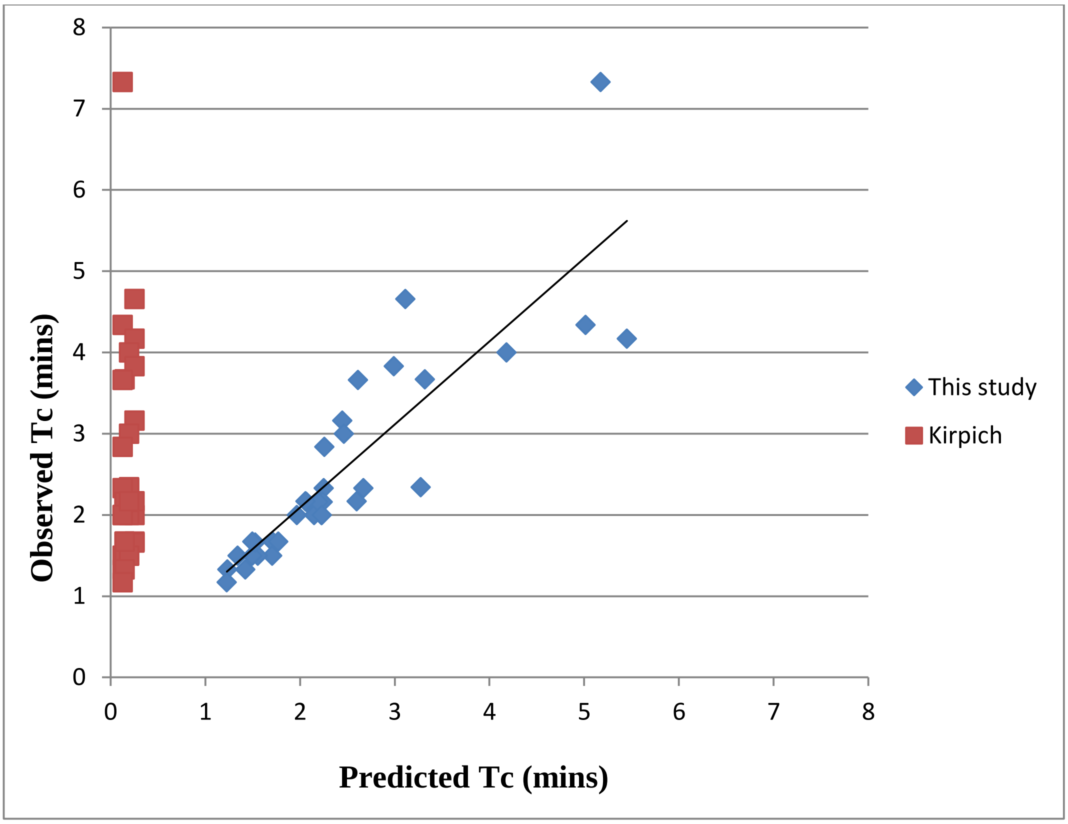

Figure 4.18 Comparison of observed results with Kirpich equation

Chapter 5 SUMMARY AND CONCLUSIONS

Experimental investigations were done to study the overland flow time parameters at different surface slopes, soil moisture and intensity of rainfall. The experiments were conducted on Advanced Hydrologic System in the Department of Hydrology, IIT Roorkee. In all 35 experiments were conducted on a plane rectangular catchment of area 2 m^2 (2m x 1m). From the present study following conclusions were made:

1. Majority of the existing models available in the literature under-predicted T_C.
2. Models such as Mathur and Perumal (2007) and Izzard (1946) were showing good results at low values of antecedent soil moisture.
3. The existing models available in the literature do not contain antecedent soil moisture (θ) parameter which has a significant role to play in determining T_C.
4. Antecedent moisture content controls the time of beginning of runoff.
5. Kirpich equation under-predicted T_C by 10 times.
6. This under-prediction of T_C by Kirpich equation may lead to over-prediction of peak discharge.
7. Variation in T_C may be attributed to the absence of a clear definition of T_C. Different researchers have defined T_C in various different ways.
8. Kirpich has given higher significance to the slope parameter whereas as per this study the slope was the least significant parameter.

5.1 CONSTRAINTS DURING THE STUDY

Although, the experiments and analysis have been done successfully, but there were some difficulties and constraints that I faced during the course of this study. Some of them are listed below

1. The sensor of the instrument was not working, so I have to use a different sensor. Hence, there might be some issues with the sensitivity of the sensor used.
2. Three out of eight spray nozzles were broken. The nozzles used to get break frequently in between the experiments. So again and again I used to get the nozzles fixed and had to wait for the nozzles to get dry and had to do experiments again.
3. The slope adjustment device was corroded, and hence it required some effort to adjust the slope.
4. Since I was also varying the moisture content of the soil, so I had to wait for the soil to get dry.

5. There were some issues with the pump and switch of the instrument. The instrument used to stop working in between the experiments, so I had to repeat the experiments again and simultaneously had to allow the soil to get dry.

Due to above mentioned constraints, even though I did many trials on the instrument but I could only get 35 meaningful events during the course of this study.

5.2 SUGGESTIONS FOR FUTURE WORK

Initially we planned of doing the experiments on the bigger rainfall simulator that was newly introduced in the Department of Hydrology, IIT Roorkee. The plan was to perform experiments on different soil types and different surfaces such as concrete, grassy surfaces, and asphalt surfaces. But due to some delay in the installation of the new rainfall simulator and due to some time constraints, the plan was dropped. Thereafter, it was decided to conduct the experiments on the old rainfall simulator i.e. Advanced hydrologic system that was available in the department. The instrument did not allow us to put anything except the sand it in. Therefore, the experiments were performed only on fine sand and hence following improvements can be made in the future studies:

1. Effect of varying length/ Area of the plot on time of concentration.
2. Effect of different soil type and surface roughness conditions on time of concentration.

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