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A Development of Travel Time Equation for Overland Flow as Affected by Vegetation

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A DEVELOPMENT OF TRAVEL TIME EQUATION FOR OVERLAND FLOW AS AFFECTED BY VEGETATION

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Civil Engineering degree and is acceptable for meeting all the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

C_v	Chezy's vegetation roughness coefficient $(\frac{\sqrt{m}}{s})$
C_b	Chezy's bed roughness coefficient $(\frac{\sqrt{m}}{s})$
T_t	Travel time (minutes)
T_c	Time of concentration (minutes)
CN	Curve number
τ_t	Total shear stress $(\frac{N}{m^2})$
τ_v	Vegetation Shear stress $(\frac{N}{m^2})$
τ_b	Bed Shear stress $(\frac{N}{m^2})$
u_0	Overland flow maximum velocity $(\frac{m}{s})$
R	Hydraulic mean radius (m)
h	Overland flow depth (m)
ρ	Density of water $(\frac{Kg}{m^3})$
g	Acceleration due to gravity $(\frac{m}{s^2})$
u_m	Overland flow mean velocity $(\frac{m}{s})$
μ	Dynamic viscosity $(\frac{N\,s}{m^2})$
i	Rainfall excess intensity $(\frac{in}{hr})$
L	Flow length (m)
S	Friction slope $(\frac{m}{m})$
S_0	Bed slope $(\frac{m}{m})$

C_d	Drag coefficient for laminar flow
N	Number of stems per square meter (m^{-2})
D	Stem diameter (m)
t	Rainfall duration (minutes)
P	Precipitation depth (m)
Q	Runoff depth (m)
q	Runoff discharge $(\frac{m^3}{minute})$
A	Flow area but assumed as watershed area for non-channelized flows (m^2)
I_a	Initial absorption losses in (m)
F	continuous absorption losses in (m)
f_v	Darcy's vegetation resistance coefficient
f_b	Darcy's bed resistance coefficient
$i_{\ total}$	Total rainfall intensity $\left(\frac{m}{hr}\right)$
S_r	Potential maximum storage retention
GLMVE	Grismer's laminar mean velocity equation $(\frac{m}{s})$
MVE	Manning's velocity equation $(\frac{m}{s})$

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

A DEVELOPMENT OF TRAVEL TIME EQUATION FOR OVERLAND FLOW AS AFFECTED BY VEGETATION

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In overland flow water research, travel time is a significant parameter used in estimating peak discharge in channels or rivers. Overland flow is assumed to be in turbulent condition to estimate travel time using Manning's Velocity Equation (MVE). When the flow is in a laminar condition, Grismer's Laminar Mean Velocity Equation (GLMVE) is applied but fails to consider the roughness parameter. A review of the literature shows numerous equations for overland travel time, but there is no known equation that determines the mean velocity of overland flow under laminar condition with a roughness coefficient or other coefficient related to the effect vegetation has on the flow. In this study, a new overland flow travel time equation was developed by assuming laminar flow and incorporating Chezy's vegetation roughness coefficient (C_v). In this paper, relationships were established between GLMVE and C_v and that relationship is used to develop a new travel time equation. The new equation was employed on theoretical models for bare soil, corn growing on the soil, and Bermuda grass growing on the soil. Standard design tables for Darcy's vegetation roughness coefficient (f_v) and Chezy's vegetation roughness coefficient (C_v) were developed for selected crops at different slopes and crop residues. Validation of the equation was performed by comparing the calculated results for travel time with published data.

CHAPTER 1: INTRODUCTION

1.1 General:

Time of concentration (T_c) is the time taken by a water droplet to travel from the farthest point in a watershed to travel along the land surface to the outlet (McCuen, 2005). Time of concentration is equal to the sum of travel times of sheet flow, shallow concentrated flow, and channel flow. Accurate estimation of travel time is necessary for the economical design of hydraulic structures and to avoid flash floods. There are many experimental and theoretical models developed to estimate travel time with some drawbacks (Henderson & Wooding, 1964, Yen & Chow, 1983, Chen & Wong, 1993, Wong, 2005, Kerby, 1959, Kirpich, 1940).

The Ganti and Burckhard travel time equation presented here is based on kinematic wave theory (Lighthill and Whitham, 1955) with fewer assumptions than those made by previous researchers (Henderson & Wooding, 1964, Yen & Chow, 1983). Many researchers dedicated their time and effort to find a vegetation roughness coefficient, for example, in the case of the SCS curve method they defined the roughness coefficient as the curve number (CN) (NRCS, 1986), The rational method contains a separate roughness coefficient based on landscape characteristics and Manning developed an equation empirically to estimate flow velocity in both natural and man-made channels i.e. $V = C\,R^{\frac{2}{3}}\,S^{\frac{1}{2}}$, but he didn't propose a new roughness coefficient instead he suggested Chezy's roughness coefficient (C) (Chezy, 1776) for Manning's velocity equation (Manning, 1889). Later, in a letter to Alfred Flamant, French hydraulician, Manning mentioned that the Chezy's roughness coefficient in MVE is almost equal to reciprocal of Kutter's roughness coefficient (n) (Manning, 1889). Manning's rejected his own formula i.e. $V = C\,R^{\frac{2}{3}}\,S^{\frac{1}{2}}$ due to difficulty in calculating cube root and dimensional homogeneity. Later Manning proposed another equation i.e. $V = C\sqrt{gS}\,[\sqrt{R} + \frac{0.22}{\sqrt{m}}(R - 0.15m)]$ in which 'm' is barometric pressure in meters mercury (Manning, 1889). Practicing engineers preferred $V = C\,R^{\frac{2}{3}}S^{\frac{1}{2}}$ instead of $V = C\sqrt{gS}\,[\sqrt{R} + \frac{0.22}{\sqrt{m}}(R - 0.15m)]$. The flow conditions for Manning's velocity equation are highly turbulent. Generally, it is assumed that overland mostly flow is laminar, and vegetation is assumed to be in a non-submerged condition.

To generate a practical expression, we need to consider laminar mean flow velocity equation and roughness coefficient for non-submerged vegetation. Manning's equation doesn't give accurate results in estimation of mean velocity in overland flow with lower slopes because MVE is presumed to apply at much greater slopes as well in watershed modelling (Grismer, 2016). Based on this, a new equation for estimating laminar flow mean velocity was proposed by Mark. E. Grismer hence referred to as Grismer's Laminar Mean Velocity Equation (GLMVE) (Grismer, 2016). Grismer neglected to consider a roughness parameter in his equation therefore a modified GLMVE is developed in this study by incorporating Chezy's roughness coefficient. The form of Chezy's roughness coefficient for non-submerged vegetation used was given by Petryk and Bosmajian (1975) of which was verified by Baptist (2007). That modified GLMVE is used to develop a travel time and flow depth equation using kinematic wave theory.

1.2 Background:

Before reviewing the literature, a few definitions are necessary. Flooding occurs when the runoff generated is more than the storage capacity of the flow surface over which the runoff is flowing. A watershed is defined as the surface area or land which contributes runoff to a defined outlet after a precipitation event. Time of concentration $(\mathbf{T_c})$ is the time taken by a water droplet to travel from the farthest point in a watershed to the outlet (McCuen, 2005). Time of concentration is a significant parameter used for estimation of peak flow in many runoff studies. Intensive research on the role of vegetation in hydrological sciences is started in 1970’s, but a gap existed between the theoretical and practical results. This gap can be minimized by using advanced technology. Particle Image Velocimetry (PIV) technology is the advanced particle tracking methodology which can be used to measure particle velocity. Henderson and Wooding (Henderson & Wooding, 1964**)**, Yen and Chow (Yen & Chow, 1983), Chen and Wong (Chen & Wong, 1993, Wong, 2005) have provided major contributions in estimating overland flow travel time.

1.3 Objective:

The purpose of this study is to understand how vegetation is affects overland flow travel time. Theoretical research is conducted by developing a new kinematic wave model based on laminar flow conditions and vegetation roughness, defined by stem density per square meter, which is compared with published experimental data and other kinematic wave models. Theoretical analysis was carried out by comparing how vegetation affects travel time and the results are validated by comparing with published experimental data. The tasks associated with this project are as follows.

1.) Development of new travel time equation based on number of stems per square meter using kinematic wave theory.

2.) To perform trend analysis between travel time and vegetation roughness. Comparing developed kinematic wave equation results with existing kinematic wave equations.

3.) Analyzing the effect of vegetation stems on overland flow travel time.

4.) Develop Chezy's and Darcy's roughness coefficient tables based on the vegetation density.

CHAPTER 2: LITERATURE REVIEW

2.1 Time of concentration:

There are two commonly accepted definitions for the time of concentration. Tc is the time taken by water droplet to travel from farthest point in the watershed to the outlet (McCuen, 2005). This is a theoretically based definition that depends on watershed characteristics; and many empirical and kinematic wave models are developed based on this definition. The second definition is based on rainfall hyetograph and resulting direct runoff hydrograph. The T_C can also be defined by the time between the center of mass of rainfall excess to the inflection point on the recession of the direct runoff hydrograph. Sometimes this definition is modified to be the time between the end of excess rainfall to the inflection point on the recession branch of a direct runoff hydrograph (McCuen, 2005).

2.2 Overland flow travel time:

Overland flow travel time is divided into sheet flow travel time and shallow concentrated flow travel time. The overland flow is occurring after completion of infiltration or saturation process, it is generally assumed to be turbulent even though it mostly representing laminar characteristics (Grismer, 2016). Various researchers have attempted to estimate accurate travel time based on kinematic wave theory, SCS method, and other empirical equations (Henderson & Wooding, 1964, Yen & Chow, 1983, Chen & Wong, 1993, Wong, 2005). Most of the researchers have assumed that the flow regime is turbulent. In general, kinematic wave equations are derived by assuming flow velocity can be estimated through Manning's equation.

2.3 Kinematic wave theory:

Kinematic wave models were first introduced by Lighthill and Whitham (1955). Kinematic wave theory is the simplified version of dynamic wave theory. The dynamic wave theory accounts for the entire spectrum of the physical processes which comprise flow in a stream or channel. Kinematic wave theory was developed by considering some physical processes (i.e. inertia and pressure forces) to be negligible.

The dynamic wave models consist of two partial differential equations i.e. conservation of mass (Continuity) and momentum (dynamic) equations they are also referred as Saint-Venant equations (Miller, 1984). The physical factors governing these equations are local acceleration, convective acceleration, hydrostatic pressure forces, gravitational forces and frictional forces.

The kinematic wave models consist of continuity equation and simplified form of momentum equation. Hence the physical factors governing these equations are gravitational forces and frictional forces.

2.3.1 Momentum equation in kinematic wave form:

The continuity equation is applicable for both kinematic and dynamic approaches. The equation of conservation of momentum can be written as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

Where Q is the discharge ($\frac{m^3}{s}$), A is the cross-sectional area (m^2), q is the lateral inflow ($\frac{m^2}{s}$), x is the space co-ordinate in the direction of flow (m) and t is the time in seconds (Chow, 1988, Mays, 1996, Schultz,1992).

The momentum equation is based on Newton’s second law of motion can be written as

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$$

Where V is the mean velocity in $(\frac{m}{s})$, y is the flow depth (m), S_0 is the bed slope, S_f is the friction slope and g is the acceleration due to gravity $(\frac{m}{s^2})$.

The simplified momentum equation in kinematic wave form can be written as

$$S_0 - S_f = 0$$

Overland flows are dominant in small watersheds such agricultural plots, rooftops, roadways, parking lots and open areas. In these watersheds, the kinematic wave is dominant in the rising branch of the hydrograph and much of the recession limb. The dynamic and diffusion portion is also rising, but these are short-term and plays a minor role (Singh. V. P, 2002). Hence kinematic wave prediction would be a better approximation for overland flow compared to dynamic wave even though dynamic flow may be dominant in some cases.

2.4 Previous research in overland flow travel time:

Previous research in overland flow travel time estimation have been done in mostly theoretical such as Kinematic wave theory (Henderson & Wooding, 1964), and in some cases experimentally such as Kirpich (1940) and Kerby (1959).

2.4.1 Soil conservation service method (Soil Conservation Services, 1986):

The volume of runoff depends on the number of factors. Certainly, rainfall volume is the most significant factor. For large watersheds, runoff volume for single storm events is dependent on the rainfall volume of previous storm events. However, for small watersheds, design hydrologists assume that the runoff volume for a single storm event is independent of previous storm events. In developing the SCS rainfall-runoff relationship the total rainfall (P) in meters is divided into three factors; direct runoff depth (Q) in meters, Actual or continuous retention of precipitation (F) in meters, and Initial abstraction (I_a) in meters. Hence the conceptual relationship between F, Q, I_a, P is as follows.

$$\frac{F}{S_r} = \frac{Q}{P-I_a}$$

S_r is potential maximum retention. The actual retention is

$$F = (P - I_a) - Q$$

Therefore, $\frac{(P-I_a)-Q}{S_r} = \frac{Q}{P-I_a}$

Hence $Q = \frac{(P-I_a)^2}{(P-I_a)+S_r}$

The retention, S_r, should be the function of five factors; land use, interception, infiltration, depression storage, and antecedent soil moisture. Empirical evidence indicated that retention and initial abstraction are related as follows.

$$I_a = 0.2S_r$$

Therefore, $Q = \frac{(P-0.2S_r)^2}{(P+0.8S_r)}$

The retention, S_r, can be calculated from the curve number (CN) which is developed through empirical analysis.

$$S_r = \frac{1000}{CN} - 10$$

Note: It is important to remember that $P \geq 0.2S_r$. When $P < 0.2S_r$ it is necessary to assume $Q = 0$.

The Soil conservation service developed a lag formula for estimating time of concentration by defining that it is time between the center of mass of excess rainfall to the peak discharge. The lag time is defined as time between peak rainfall to peak discharge in direct runoff hydrograph. The SCS method also indicates that time of concentration is equal to 1.67 time of the lag time.

Limitations of SCS method (Soil Conservation Service, 1986):

- This method should be used on watersheds that are homogeneous in CN.
- The graphical method can be used only when CN is 50 or greater.
- The computed value of $\frac{I_a}{P}$ should be 0.1 to 0.5.
- This method should be used when watershed has one main channel otherwise hydrograph method should be used.

The adopted equations for estimating travel time based on watershed characteristics and limitations are as follows.

2.4.2 Hathway-Kerby equation (Kerby, 1959):

This equation can be used for small watersheds which are less than 40468.6 m^2 and flow length should be less than 0.37 km. Kerby developed a nomograph to estimate time of concentration in watershed.

$$T_t = 1.441 {N_f}^{0.467} L^{0.467} S^{-0.233}$$

T_t=Travel time in minutes,

N_f = flow retardance factor,

L = overland flow length, (m)

S = overland flow path slope, $({}^{m}/{}_{m})$

2.4.3 Kirpich equation (Kirpich, 1940):

This equation can be used for watersheds less than 453248 m^2 and slope is in between 0.03 to 0.1. Kirpich equation is experimentally developed by only six data points and it is independent of roughness parameter and rainfall excess intensity which is in sufficient for estimating accurate travel time.

T_t = 2.495K$L^{0.77}S^{Y}$

For Tennessee K = 0.0078, Y= -0.385

For Pennsylvania K = 0.0013, Y = -0.5

T_t=Travel time in minutes,

L = Length of channel/ditch from head water to outlet, m

S = average watershed slope, ($^{m}/_{m}$)

2.4.4 Yen and chow equation (Yen & Chow, 1983):

This equation can be used for small watersheds and it is developed based on kinematic wave theory. Yen and Chow equation is independent up on intensity and it is developed based on Manning's velocity equation which is developed based turbulent condition.

$T_t = 1.2\ (\frac{n\,L}{S^{0.5}})^{0.6}$

The above formula is derived from "Woalhiser and Liggetts" (Woalhiser and Liggetts, 1967)

$T_t = 7(\ \frac{n^{0.6}L^{0.6}}{S^{0.3}i^{0.4}})$

By substituting i = 80mm/hr. we get

$T_t = 1.2\ (\frac{n\,L}{S^{0.5}})^{0.6}$

Where L = Length of overland flow (m)

n = Manning's roughness coefficient.

T_t = Travel time in minutes.

S = overland slope (m/m)

i = Intensity (mm/hr.).

2.4.5 Henderson-Wooding equation (Henderson and wooding, 1964):

This equation is developed based on kinematic wave theory for flow in overland area. It is based on Manning's velocity equation which is developed based turbulent condition.

$$T_t = 0.44\ (Ln)^{0.6}\ S^{-0.3}\ i^{-0.4}$$

Where T_t = Travel time in minutes.

n = Manning's roughness coefficient.

L = Longest overland flow length, (m)

S = Average overland flow path slope, $({}^{m}/_{m})$

i = Intensity$(\frac{m}{hr})$.

CHAPTER 3: METHODOLOGY

3.1 Watershed characteristics:

The concept of a watershed is the basic for many hydrologic designs. Generally, large watersheds are the summation of small watersheds, in that any rainfall occurring in the region of outlet will contribute runoff to that outlet. The entire contributing region is termed as a watershed. In general, every watershed has its characteristics like length, shape, drainage area, slope, roughness, land cover and use.

3.1.1 Drainage area:

The drainage area, A, is the most significant watershed parameter used to estimate runoff generation for a storm event. The volume of runoff produced is equal to the product of rainfall depth and drainage area, by considering this assumption this parameter is widely used in linear models (McCuen, 2005). The drainage area can be estimated after delineation of the watershed using planimeter or by grid area method.

3.1.2 Watershed length:

The length of the watershed, L is the significant parameter in estimating time of concentration, usually, the length of the watershed is the distance between the farthest point in contributing drainage area to the watershed outlet (McCuen, 2005).

3.1.3 Watershed slope:

The slope of the watershed, S, is defined as the ratio of the difference in elevation between endpoints of the principal flow path along the hydrologic flow length (McCuen, 2005). Usually in overland flow, the difference in elevation can be estimated using contour maps.

$$S = \frac{\nabla E}{L}$$

Where ∇E = Change in elevation.

L = Hydrologic flow length.

3.1.4 Land cover and use:

Runoff generated in a grass surface has less velocity compared to bare soil due to more hydraulically resistance or roughness. Most frequently, the Rational method is used for watersheds within 24 acres it uses land cover coefficient as runoff coefficient 'C' (McCuen, 2005). The soil conservation service (1986) has developed another coefficient based on soil type, antecedent soil moisture and land use i.e. curve number (CN) (McCuen, 2005).

3.1.5 Surface Roughness (n):

Surface roughness is the unevenness of texture, it is more important in hydrological design. Manning's roughness coefficient is the most widely used roughness index (Henderson and wooding, 1964, Yen & Chow, 1983 and Woalhiser and Liggetts, 1967). In this study, the Manning's roughness is ranging from 0.02 to 0.41.

3.2 Mathematical model for overland flow travel time using kinematic wave theory:

The total shear stress on the fluid can be estimated by using conservation of momentum principle for uniform and steady flow conditions is as follows (Whipple, 2004).

$$\tau = \rho g R S$$

By assuming $S = S_0$, R $\approx h$ for wide rectangular channels

$$\text{Therefore,} \ \tau = \rho g h S_0$$

Where τ = Total shear stress $(\frac{N}{m^2})$, ρ = Density of water $(\frac{Kg}{m^3})$ = 1000, g = Acceleration due to gravity $(\frac{m}{s^2})$ = 9.81, R = Hydraulic mean radius (m), S = Friction slope, $(\frac{m}{m})$, S_0 = Bed slope, $(\frac{m}{m})$ and h = Overland flow depth (m).

Most of the watershed modeling and estimation of overland flow velocity is assumed as the turbulent flow, even though the flow is under laminar flow conditions. Under steady and laminar flow conditions the surface flow velocity is nearly proportional to slope rather than the square root of the slope. Grismer developed laminar mean flow velocity equation which is represented as (Grismer, 2016).

$$u_m = \left(\frac{\rho g h^2}{3\mu}\right) Sin\theta \ \simeq (0.7524\rho g h^2/3\mu){S_0}^{0.983} \qquad (1)$$

Based on best fitting power curve $Sin\theta$ is represented as ${S_0}^{0.983}$ and 0.7524 value came from converting $Sin\theta$ to ${S_0}^{0.983}$.

Where μ= Dynamic viscosity $(\frac{N\,s}{m^2})$ and u_m = Overland flow mean velocity $(\frac{m}{s})$

But in equation (1) we are missing roughness parameter, required to introduce roughness parameter into equation (1).

i.e. $\tau = K\,u_m^2$ where ($Constant\ (K) = \frac{1.5\rho}{R_e}$) (Baptist et al. 2007)

$$\mathrm{u_m} = \sqrt{\frac{\rho g h S_0}{K}} = C_v\sqrt{hS_0}$$

Therefore, $\frac{\rho g h}{3\mu} = \frac{{C_v}^2}{2u_m}$ (2)

Substitute equation (2) is equation (1) to modify Grismer's laminar mean velocity equation

$$u_m = 0.6133C_v\sqrt{h\,{S_0}^{0.983}} \qquad (3)$$

Now travel time could be estimated using equation (3)

Travel time $(T_t) = \frac{L}{60*\,u_m}$ (Since dividing with 60 to convert seconds to minutes)

$$T_t = \frac{0.026\mathrm{L}}{C_v\sqrt{hS_0^{0.983}}}$$

Where flow depth, h, is an unknown parameter, as per kinematic wave theory, flow depth is the product of rainfall excess intensity, if absorption losses are considered, or rainfall intensity if no absorption losses are considered, and travel time (Miller, 1984).

$$h_{(m)} = \frac{i\,T_t}{60} \qquad \text{(Since 60 is to convert minute to hour)}$$

i.e. $$h_{(m)} = \frac{i\,T_t}{60}$$

$$h_{(m)} = \frac{i}{60}\,\frac{L}{60*u_m}$$

$$h_{(m)} = \left(\frac{i\,L}{2207.88\,C_v\,\sqrt{{S_0}^{0.983}}}\right)^{\frac{2}{3}} \qquad (4)$$

Therefore, final travel time equation for overland flow is

$$T_t = \frac{0.3385\,L^{2/3}}{{C_v}^{2/3}\,i^{1/3}\,{S_0}^{0.324}} \qquad (5)$$

Where C_v in equation (5) is estimated using Petryk and Bosmajian (1975) equation and verified by Baptist (2007)

$$C_v = \sqrt{\left(\frac{1}{\frac{1}{C_b^2}+\frac{C_d N d h}{2g}}\right)}$$

Where C_v = Chezy's vegetation resistance coefficient ($\frac{\sqrt{m}}{s}$), C_b = Chezy's bed resistance coefficient ($\frac{\sqrt{m}}{s}$) $\approx \sqrt{\frac{8g}{f_b}}$, i = Rainfall excess intensity ($\frac{m}{hr}$), L = Flow length (m), T_t= Travel time (minutes), N = Number of stems per square meter (m^{-2}), D = Stem diameter (m), f_b = Darcy's bed resistance coefficient and it can be estimated using experimentation, f_v = Darcy's vegetation resistance coefficient and C_d= Drag coefficient for laminar flow.

To estimate flow depth in equation (4), we need to know C_v which is unknown parameter, so by considering $C_v \approx \sqrt{\frac{8g}{f_v}}$ (Baptist et al. 2007) flow depth equation can be written as.

$$h \approx \frac{i^{2/3}\, L^{2/3}\, {f_v}^{1/3}}{725.94\, {S_0}^{0.3276}}$$

3.3 Estimation of Rainfall excess intensity based on curve number (CN):

As per SCS curve number method runoff depth can be estimated as

Runoff discharge $\left(q_{\left(\frac{m^3}{minute}\right)}\right) = \frac{volume}{time} = \frac{A_{(m^2)} h_{(m)}}{T_{t(minutes)}}$

By substituting ($h_{(m)} = \frac{iT_t}{60}$) in runoff discharge (q) equation

$$q_{(\frac{m^3}{minute})} = \frac{A_{(m^2)} i_{(m/hr)}}{60}$$

Rainfall excess intensity $(i_{(\frac{m}{hr})}) = \frac{60 * q_{(\frac{m^3}{minute})}}{A_{(m^2)}}$ (6)

In equation (6) runoff discharge is unknown parameter, to estimate that as per conceptual model

Runoff discharge $(q_{(\frac{m^3}{minute})})$ = precipitation discharge – losses discharge

$$q_{(\frac{m^3}{minute})} = \frac{A_{(m^2)} i_{total(\frac{m}{hr})}}{60} - \frac{(F+I_a)_{(m)} A_{(m^2)}}{t_{(minutes)}} \qquad (7)$$

According to the SCS developed rainfall-runoff relationship as Initial and continuous absorption losses are equal to the difference between precipitation and runoff generated (McCuen, 2005).

$F + I_a = P - Q = P - \frac{(P - I_a)^2}{(P - I_a) + S_r}$ (Since $Q = \frac{(P - I_a)^2}{(P - I_a) + S_r}$ stated in the literature review)

Where S_r can be estimated as $S_r = \frac{1000}{CN} - 10$, $I_a = 0.2S_r$

Hence by substituting equation (7) in to equation (6) an equation to estimate rainfall excess intensity results.

Therefore, Rainfall excess intensity $(i_{(\frac{m}{hr})}) = i_{total_{(\frac{m}{hr})}} - \frac{60*(F+I_a)_{(m)}}{t_{(minutes)}}$

Where t = Rainfall duration (minutes), q = Runoff discharge $(\frac{m^3}{minute})$, A = Flow area but assumed as watershed area for non-channelized flows (m^2), i_{total} = Total rainfall intensity $(\frac{m}{hr})$ and CN = Curve number.

3.4 Mathematical model for Darcy's vegetation resistance based on stem density and diameter is as follows:

Total shear stress $(\tau_t) = \tau_b + \tau_V$

Where τ_b = Bed shear stress $(\frac{N}{m^2})$, τ_v = Vegetation shear stress $(\frac{N}{m^2})$.

$$\rho g R S_0 = \rho g h S_0 = \rho g \frac{{u_m}^2}{C_b^2} + \frac{\rho C_d N D h {u_m}^2}{2}$$

$$h S_o = {u_m}^2 [\frac{1}{C_b^2} + \frac{C_d N D h}{2g}]$$

$$\therefore \quad {u_m}^2 = \frac{h S_0}{[\frac{1}{C_b^2} + \frac{C_d N D h}{2g}]} \quad (8)$$

Substituting Darcy's vegetation resistance $(f_v) = \frac{8gRS_0}{{u_m}^2} = \frac{8ghS_0}{{u_m}^2}$ (Gilley et al. 1992)

$$f_v = 8g[\frac{1}{C_b^2} + \frac{C_d N D h}{2g}]$$

$$f_v = 8g\left[\frac{f_b}{8g} + \frac{C_d N D h}{2g}\right]$$

By taking Least count multiple of $8g$

$$f_v = f_{b+} 4 C_d N D h \quad (9)$$

3.5 Model Verification:

The flow length and slope are arbitrary values in table 3.1 and 3.2. Curve number is based on soil type and vegetation type. The number of stems per square meter and stem diameter is selected based on Gilley et al. (1994). The number of stems per square meter and stem diameter of Bermuda grass is defined as an average value due to the lack of data for a dense, medium and poor condition.

Table 3.1 Theoretical inputs for estimating excess rainfall intensity, flow depth and travel time

Land cover	Flow length (meters)	Slope (%)	Curve number	Manning's roughness (n)	no. of Stems per sq.m	Stem diameter(meter)
Bare soil	30.48	8	94	0.02	0	0
Corn	30.48	8	89	0.05	6.56	0.0029
Bermuda grass	30.48	8	85	0.41	1640	0.001700001

Table 3.2 Theoretical inputs for developed Chezy's and Darcy's – Weisbach vegetation roughness coefficient tables

Type	I (25-yr precipitation) (m/hr)	flow length (m)	drag coefficient (Cd)	No. of stems per m (N)	Avg stem dia (D) in (m)
Gravel bed	0.00424628	30.48	2.075	0	0
Corn	0.00424628	30.48	2.075	6.56	0.0029
Soyabeans	0.00424628	30.48	2.075	29.5	0.00086
Wheat	0.00424628	30.48	2.075	197	0.00071
Sorghum	0.00424628	30.48	2.075	23	0.0034
Sunflower	0.00424628	30.48	2.075	6.56	0.00152
Cotton	0.00424628	30.48	2.075	13.1	0.0031
Bermuda grass	0.003272253	30.48	2.075	1640	0.001700001

3.6 Assumptions:

- Rainfall occurred over the entire basin; otherwise, individual travel time estimation required a summing up of all individual travel times to obtain final travel time. Uniform rainfall resulted in excess intensity.

- Runoff area is assumed to be the whole watershed area.
- Friction slope is equal to the bed slope.
- Flow is perpendicular to the crops.
- Pressure forces and acceleration were not considered.
- Soil is in dry condition before storm event.
- Results were developed based on rainfall's excess intensity and length as constants for different crops due to lack of Curve Number (CN) data for different crops.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Travel time:

Figure 4.1, 4.2 and 4.3 illustrates overland flow travel time results generated based on theoretical inputs and design storm intensities from Intensity-Duration-Frequency curves for return periods of 2-yr, 5-yr, 10-yr, 25-yr for 24-year storm event. The flow retardance factor values are 0.1 for bare soil, 0.2 for corn and 0.8 for Bermuda grass. The increase in rainfall excess intensity leads to decrease in travel time. From the obtained results, the values obtained using the Henderson and Wooding equation have the highest travel time compared to other equations in bare and vegetated conditions. The difference in travel time between Henderson and Wooding equation and the Ganti and Burckhard equation is increasing with vegetation stems per square meter. Hence Kirpich – Pennsylvania, Kirpich – Tennessee, and Hathway-Kerby are giving same travel time value for any precipitation.

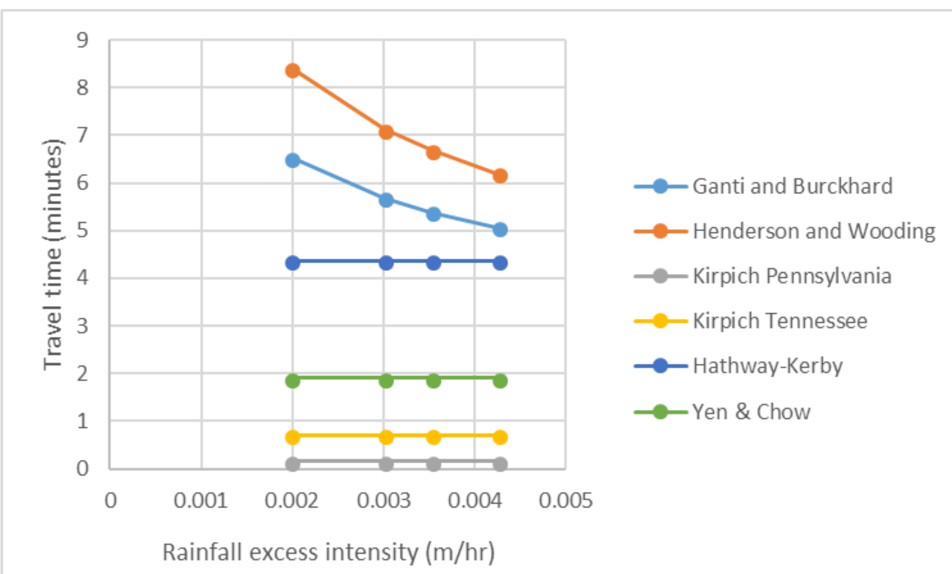

Figure 4.1 Overland flow travel time at Bare soil condition

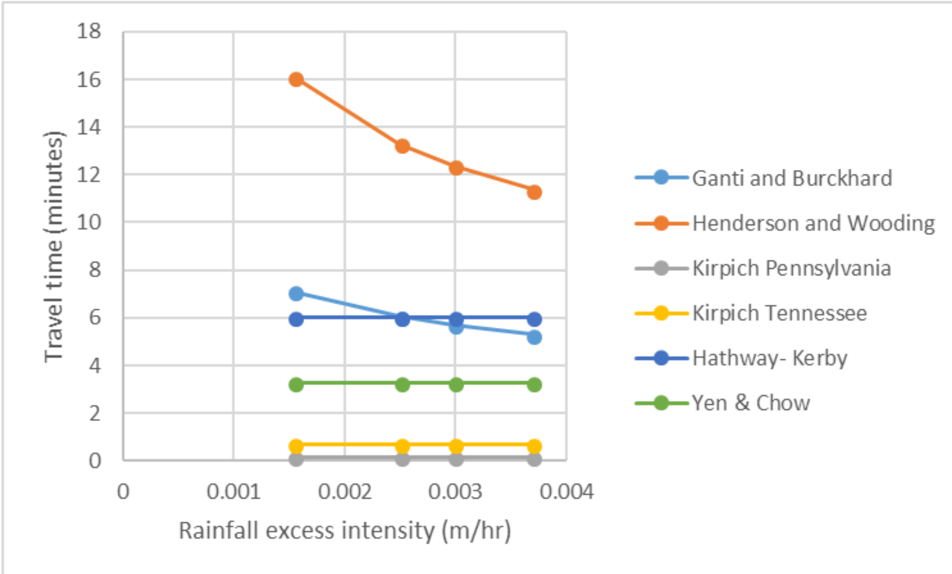

Figure 4.2 Overland flow travel time at corn crop condition

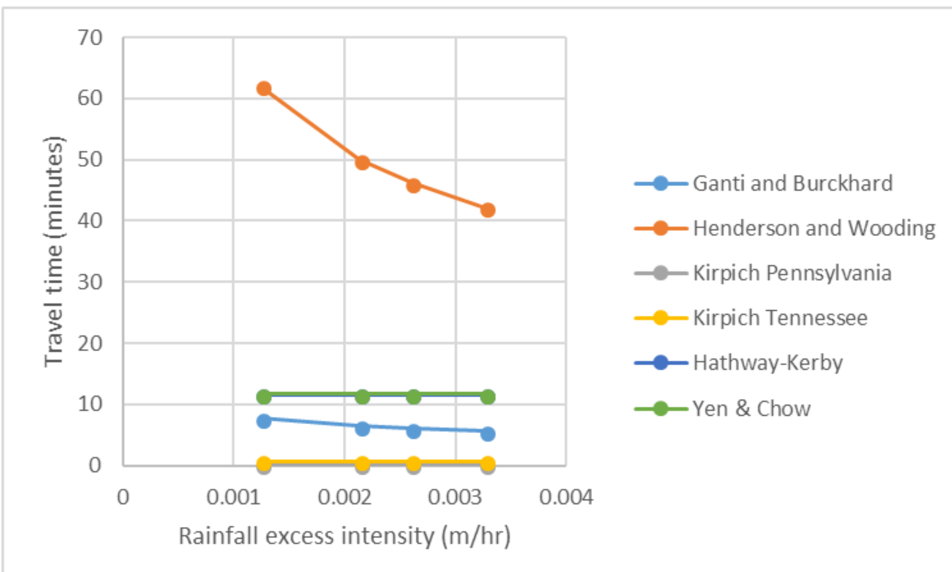

Figure 4.3 Overland flow travel time at Bermuda grass condition

4.2 Reynolds number:

Reynolds number is the only parameter which defines flow condition in fluid mechanics. In this study, overland flow was assumed to be laminar in order to develop the travel time equation. The results observed from theoretical inputs for bare soil, Corn and Bermuda grass conditions for all equations except the Kirpich-Pennsylvania equation indicate the flow is in laminar condition with $R_e < 500$. Kirpich is developed travel time equation empirically based on six data points which are very insufficient to obtain the accurate result. There is no roughness parameter is considered in Kirpich equation to estimate travel time, hence it gives the same value for any type of land cover. In Figure 4.4 Reynolds number decreases with increase in vegetation density hence travel time increases.

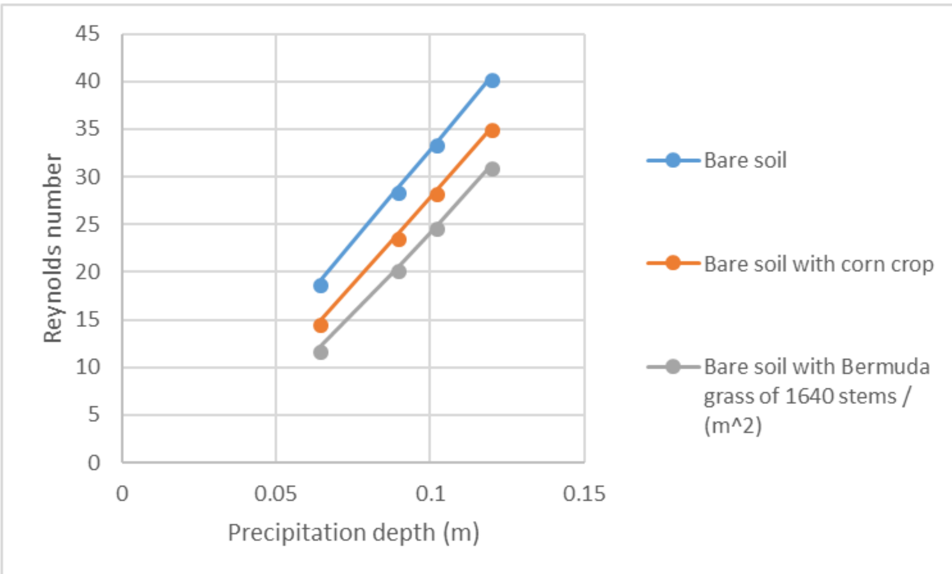

Figure 4.4 Overland flow Reynolds number based on vegetation type at 8% slope

4.3 Flow depth:

Flow depth is a significant parameter in estimating overland flow travel time, but it is highly complicated to measure in overland flow. There is no known equation to estimate overland flow depth in literature without knowing overland travel time. Hence a theoretical equation is developed based on laminar flow conditions which are applicable for both bare and vegetation condition using kinematic wave theory. Figure 4.5 shows flow depth is increasing with precipitation depth at same land cover. Flow depth is greater in bare soil compared to Corn and Bermuda grass condition because infiltration rate is higher in vegetation condition compared to bare soil.

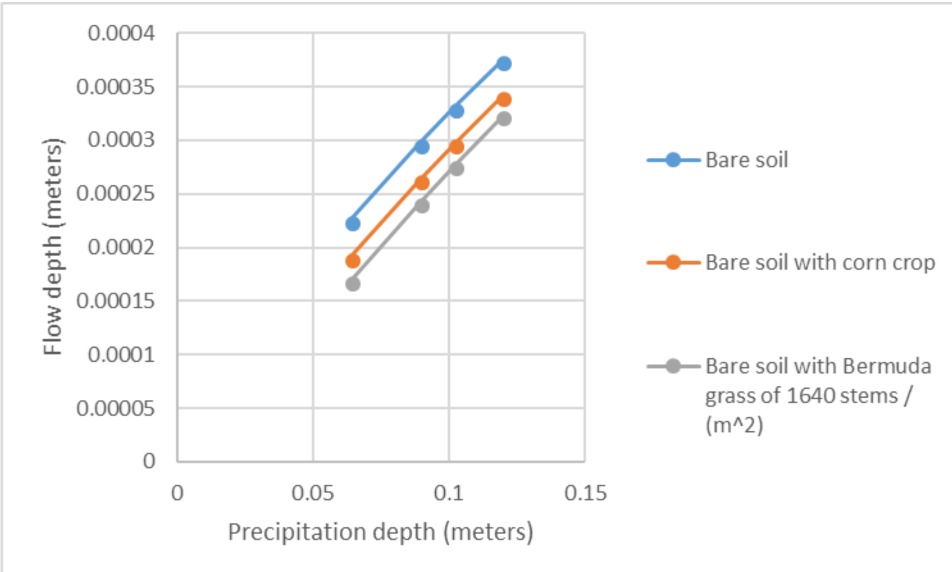

Figure 4.5 Overland flow depth based on stem density per square meter at 8% slope.

4.4 Roughness coefficients:

Assumptions made in order to calculate roughness coefficients are as follows.

- Darcy's friction factor at no vegetation condition (f_b) and Chezy's roughness coefficients at no vegetation condition (C_b) values are assumed to be constant with respect to slope for concrete, asphalt and bare soil surfaces.
- 'f_b' values for bare soil are selected from Gilley et al. (1992) at perpendicular flow condition. Table 4.1 and 4.2 for Selected crops are developed based on $f_v = f_{b+}4C_dNDh$ and 'C_v' under non-submerged vegetation condition by Baptist et al. 2007. Flow is assumed to be perpendicular to the crops.
- Drag coefficient is chosen based on the average value of Reynold's number for the laminar flow condition results of Xiao-guang Liu and Yu-hong Zeng (2016).

Variation of roughness coefficient is as follows.

Figure 4.7 represents 'f_v' decreases with increase in slope due to increase in mean velocity of flow.

Figure 4.6 represents 'f_v' increases with increase in crop residue.

Figure 4.8 represents 'C_v' increases with Increase in slope.

Figure 4.9 represents 'C_v' decreases with increase in crop residue.

Literature review includes experimentally determined 'f_v' values for selected crops at a particular slope (Gilley et al. 1994). Gilley et al. (1992) developed 'f_b' values for different crop residues at bare soil condition. In this study, the 'f_v' table is extended to different slopes with different crop residues for selected crops based on theoretically developed 'f_v' equation. The range of values for f_v are from 0.049 to 6.37 and C_v is from 3.5 to 39.62.

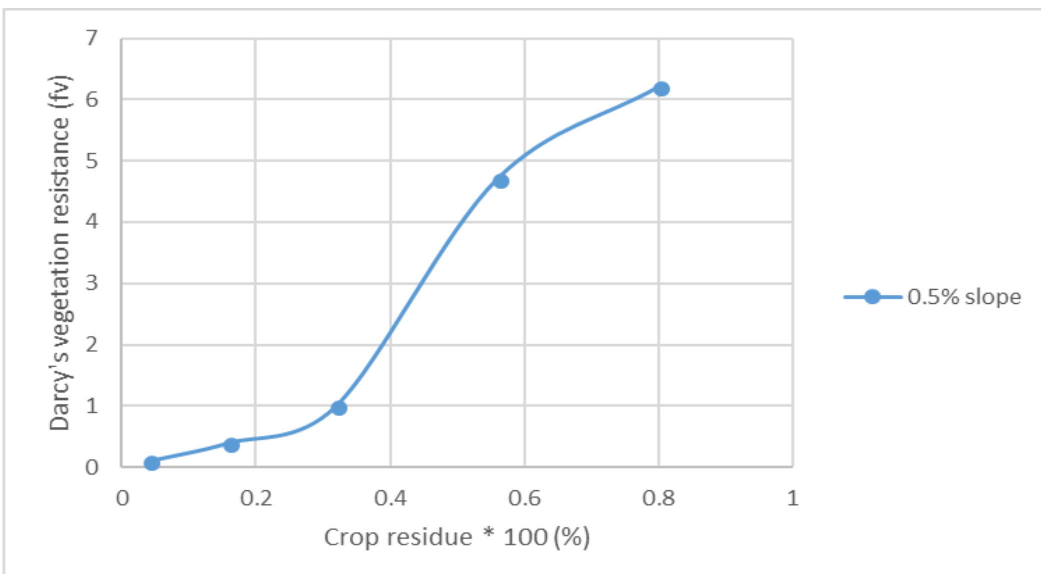

Figure 4.6 Darcy's vegetation roughness values for corn based on crop residue

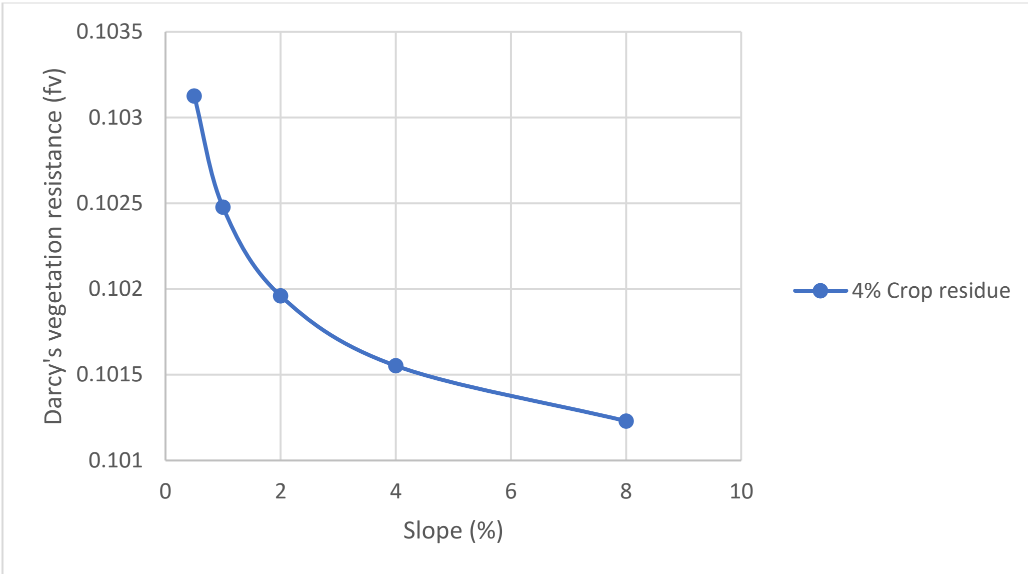

Figure 4.7 Darcy’s vegetation roughness values for corn based on slope

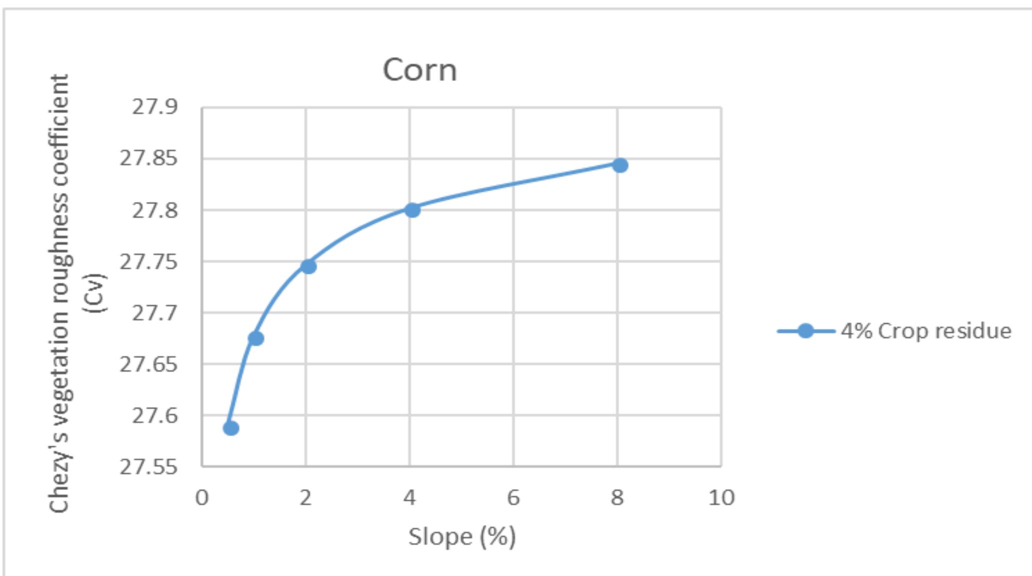

Figure 4.8 Chezy’s vegetation roughness values based on slope

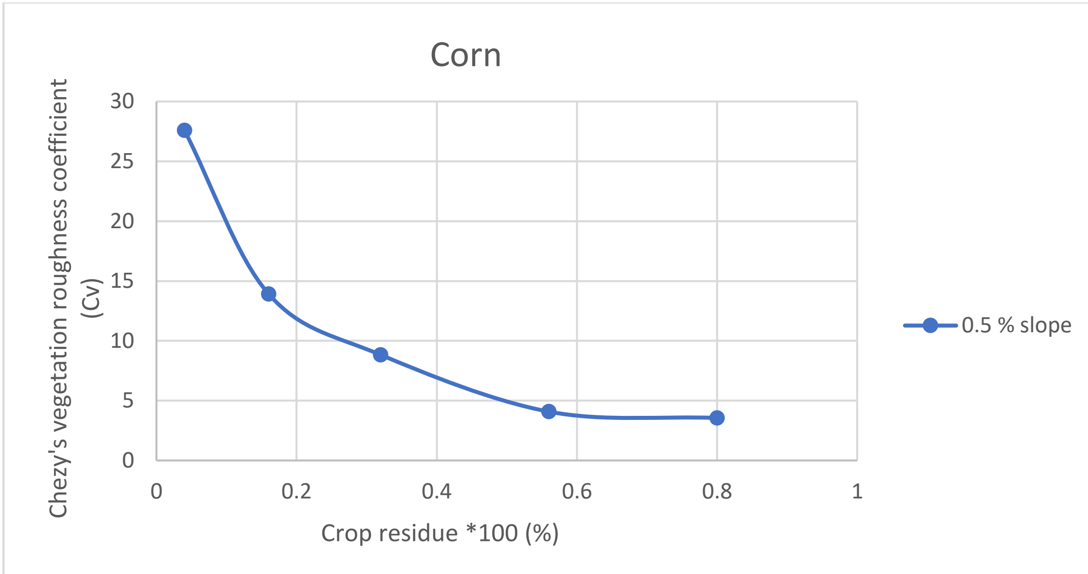

Figure 4.9 Chezy's vegetation roughness values based on crop residue

Table 4.1 Darcy's – Weisbach vegetation roughness coefficient table for selected crops based on f_b in Gilley et.al, 1992

At slope 0.005	4% C.R	16% C.R	32% C.R	56% C.R	80% C.R
	fv	fv	fv	fv	fv
Concrete	0.049993	0.1999701	0.499924	2.3496407	3.099526
Asphalt	0.06999	0.2799581	0.699894	3.289497	4.3393365
Bare soil (Gravel)	0.1	0.4	1	4.7	6.2
Corn	0.103127	0.4051258	1.006834	4.7112199	6.2121913
Soyabeans	0.103259	0.4053399	1.007119	4.7116883	6.2127003
Wheat	0.111001	0.4174777	1.023306	4.7381583	6.2414847
Sorghum	0.107385	0.4118944	1.01586	4.7259996	6.2282591
Bermuda grass (Representing pasture)	0.150516	0.4740357	1.097957	4.8616453	6.3760874
Sun flower	0.103758	0.4051949	1.006932	4.7113809	6.2123662
Cotton	0.102998	0.4041478	1.005534	4.7090876	6.2098739
At slope 0.01	fv	fv	fv	fv	fv
Concrete	0.049993	0.1999701	0.499924	2.3496407	3.099526
Asphalt	0.06999	0.2799581	0.699894	3.289497	4.3393365
Bare soil (Gravel)	0.1	0.4	1	4.7	6.2
Corn	0.102477	0.4040671	1.005422	4.7089045	6.2096749
Soyabeans	0.102582	0.404237	1.005649	4.7092762	6.2100788
Wheat	0.108679	0.4138565	1.018478	4.7302774	6.2329115
Sorghum	0.105836	0.4094336	1.012579	4.7206318	6.2224223
Bermuda grass (Representing pasture)	0.13906	0.458095	1.077257	4.8281193	6.3394958
Sun flower	0.102513	0.4041255	1.0055	4.7090322	6.2098137
Cotton	0.102001	0.4032937	1.004391	4.7072123	6.207836
At slope 0.02	fv	fv	fv	fv	fv
Concrete	0.049993	0.1999701	0.499924	2.3496407	3.099526
Asphalt	0.06999	0.2799581	0.699894	3.289497	4.3393365
Bare soil (Gravel)	0.1	0.4	1	4.7	6.2
Corn	0.10196	0.4032273	1.004303	4.7070671	6.2076782
Soyabeans	0.102043	0.4033621	1.004482	4.707362	6.2079987
Wheat	0.106828	0.4109889	1.014653	4.7240256	6.2261125
Sorghum	0.104604	0.4074834	1.009978	4.7163729	6.2177923
Bermuda grass (Representing pasture)	0.130336	0.4456896	1.06101	4.8015784	6.3105511
Sun flower	0.101989	0.4032736	1.004364	4.7071684	6.2077883
Cotton	0.101585	0.4026137	1.003484	4.7057241	6.2062189
At slope 0.04	fv	fv	fv	fv	fv
Concrete	0.04999251	0.19997006	0.49992441	2.34964069	3.09952605
Asphalt	0.06998952	0.27995808	0.69989417	3.28949696	4.33933647
Bare soil (Gravel)	0.1	0.4	1	4.7	6.2
Corn	0.10155244	0.40256102	1.00341425	4.70560883	6.20609367
Soyabeans	0.10161779	0.40266795	1.00355682	4.7058429	6.20634801
Wheat	0.10538143	0.40871627	1.01162184	4.71906564	6.22071961
Sorghum	0.10363583	0.40593695	1.00791554	4.71299357	6.21411898
Bermuda grass (Representing pasture)	0.12454483	0.43599922	1.04822848	4.78055482	6.28763946
Sun flower	0.10157489	0.40259777	1.00346324	4.70568927	6.20618107
Cotton	0.10125543	0.40207417	1.00276517	4.70454304	6.20493564
At slope 0.08	fv	fv	fv	fv	fv
Concrete	0.04999251	0.19997006	0.49992441	2.34964069	3.09952605
Asphalt	0.06998952	0.27995808	0.69989417	3.28949696	4.33933647
Bare soil (Gravel)	0.1	0.4	1	4.7	6.2
Corn	0.10122997	0.40203238	1.00270946	4.70445154	6.20483623
Soyabeans	0.10128166	0.40211723	1.00282258	4.70463731	6.20503807
Wheat	0.10424678	0.40691459	1.0092192	4.71513023	6.21644144
Sorghum	0.10287421	0.40471054	1.00628023	4.710312	6.21120452
Bermuda grass (Representing pasture)	0.11910247	0.42933839	1.03912663	4.7638893	6.26949332
Sun flower	0.10124773	0.40206154	1.00274833	4.70451538	6.20490559
Cotton	0.10099499	0.40164607	1.00219443	4.70360569	6.20391721

Table 4.2 Chezy's vegetation resistance coefficient table based on Baptist et al. 2007

At slope 0.005	4% C.R	16% C.R	32% C.R	56% C.R	80% C.R
Type	Cv	Cv	Cv	Cv	Cv
Concrete	39.62114	19.8106	12.5293	5.77935	5.0319
Asphalt	33.48598	16.743	10.5892	4.88444	4.25273
Bare soil (Gravel)	28.01638	14.0082	8.85956	4.08661	3.55808
Corn	27.59068	13.9231	8.83026	4.08178	3.55459
Soyabeans	27.57316	13.9195	8.82904	4.08158	3.55445
Wheat	26.61268	13.7223	8.76067	4.07026	3.54624
Sorghum	27.04661	13.8123	8.79195	4.07545	3.55
Bermuda grass (Representing pasture)	22.83634	12.8678	8.45509	4.01842	3.50861
Sun flower	27.58386	13.9218	8.82984	4.08172	3.55454
Cotton	27.67021	13.9392	8.83582	4.0827	3.55525
At slope 0.01	4% C.R	16% C.R	32% C.R	56% C.R	80% C.R
Type	Cv	Cv	Cv	Cv	Cv
Concrete	39.62114	19.8106	12.5293	5.77935	5.0319
Asphalt	33.48598	16.743	10.5892	4.88444	4.25273
Bare soil (Gravel)	28.01638	14.0082	8.85956	4.08661	3.55808
Corn	27.67762	13.9406	8.83629	4.08278	3.55531
Soyabeans	27.66363	13.9377	8.83532	4.08262	3.5552
Wheat	26.89246	13.7805	8.78092	4.07362	3.54868
Sorghum	27.24203	13.8523	8.80583	4.07775	3.55167
Bermuda grass (Representing pasture)	23.75914	13.0898	8.53594	4.03233	3.51872
Sun flower	27.67281	13.9396	8.83596	4.08272	3.55527
Cotton	27.74145	13.9534	8.84071	4.08351	3.55584
At slope 0.02	4% C.R	16% C.R	32% C.R	56% C.R	80% C.R
Type	Cv	Cv	Cv	Cv	Cv
Concrete	39.62114	19.8106	12.5293	5.77935	5.0319
Asphalt	33.48598	16.743	10.5892	4.88444	4.25273
Bare soil (Gravel)	28.01638	14.0082	8.85956	4.08661	3.55808
Corn	27.74695	13.9545	8.84108	4.08357	3.55588
Soyabeans	27.7358	13.9522	8.84031	4.08344	3.55579
Wheat	27.11816	13.827	8.79705	4.0763	3.55062
Sorghum	27.39886	13.8843	8.81687	4.07957	3.55299
Bermuda grass (Representing pasture)	24.54089	13.2707	8.60105	4.04343	3.52678
Sun flower	27.74311	13.9537	8.84082	4.08353	3.55585
Cotton	27.7978	13.9646	8.84459	4.08415	3.5563
At slope 0.04	4% C.R	16% C.R	32% C.R	56% C.R	80% C.R
Type	Cv	Cv	Cv	Cv	Cv
Concrete	39.62114	19.8106	12.5293	5.77935	5.0319
Asphalt	33.48598	16.743	10.5892	4.88444	4.25273
Bare soil (Gravel)	28.01638	14.0082	8.85956	4.08661	3.55808
Corn	27.80218	13.9655	8.84489	4.0842	3.55634
Soyabeans	27.7933	13.9637	8.84428	4.0841	3.55626
Wheat	27.29953	13.8641	8.80989	4.07842	3.55215
Sorghum	27.5244	13.9097	8.82565	4.08102	3.55404
Bermuda grass (Representing pasture)	25.18884	13.4174	8.65334	4.05227	3.5332
Sun flower	27.79912	13.9649	8.84468	4.08416	3.55631
Cotton	27.84266	13.9736	8.84767	4.08465	3.55667
At Slope 0.08	4% C.R	16% C.R	32% C.R	56% C.R	80% C.R
Type	Cv	Cv	Cv	Cv	Cv
Concrete	39.6211434	19.81057	12.529315	5.779347	5.031898
Asphalt	33.485978	16.74299	10.589204	4.88444	4.25273
Bare soil (Gravel)	28.0163792	14.00819	8.859557	4.086609	3.558084
Corn	27.846143	13.9743	8.8479125	4.084693	3.556697
Soyabeans	27.8390774	13.97289	8.8474271	4.084613	3.556639
Wheat	27.444909	13.8936	8.8200955	4.080107	3.553376
Sorghum	27.6247142	13.92991	8.8326261	4.082175	3.554873
Bermuda grass (Representing pasture)	25.7322417	13.53545	8.6951658	4.059318	3.538311
Sun flower	27.8437145	13.97382	8.8477457	4.084666	3.556677
Cotton	27.8783533	13.98073	8.8501229	4.085057	3.55696

4.5 Experimental Validation:

The Ganti and Burckhard equation is tested based on experimentally published data by H. Madi et.al (2013). The drag coefficient value is assumed to be 2.075 based on the assumption of laminar flow condition and bed slope fixed at 3^0. The C_b value is taken as 28.016 and rainfall intensity is 73 $\frac{mm}{hr}$(i.e. 2.87402 $\frac{in}{hr}$). There is an increase in stem density leads to a decrease in mean velocity. C_v decreased by 19.51% from bare soil to 2500 stems per square meter condition, which is shown in Figure 4.12. From the Figure 4.11, Ganti and Burckhard equation and Yen and Chow's (1983) is giving less than 50% deviation from the actual value. Ganti and Burckhard equation has an average of 38% difference in travel time compared to experimental data, Henderson and Wooding's equation is 60.086%, Yen & Chow is 22.1%, Kirpich-Pennsylvania equation is 96.08% and Kirpich – Tennessee equation is 83.25%. Travel time equations developed using MVE shows an identical trend but the Ganti and Burckhard equation using C_v shows in increases with an increase in stem density, which is shown in Figure.4.10. The decrease in travel time values based on MVE shown in Figure.4.10 is due to variation in selecting the range of n values by H. Madi et.al (2013) but in Ganti and Burckhard equation the travel time trend shows increasing because of replacing n with C_v.

Table 4.3 Experimental validation inputs

Length(m)	Slope	Rainfall intensity (m/hr)	Number of stems/(m^2)	Sem diameter (m)	Measured Flow depth (m)	n
2	0.0524	0.073000108	0	0.004	0.000537	0.0158
2	0.0524	0.073000108	126	0.004	0.00068	0.0245
2	0.0524	0.073000108	203	0.004	0.000722	0.0278
2	0.0524	0.073000108	461	0.004	0.000721	0.027
2	0.0524	0.073000108	2500	0.004	0.00086	0.0379

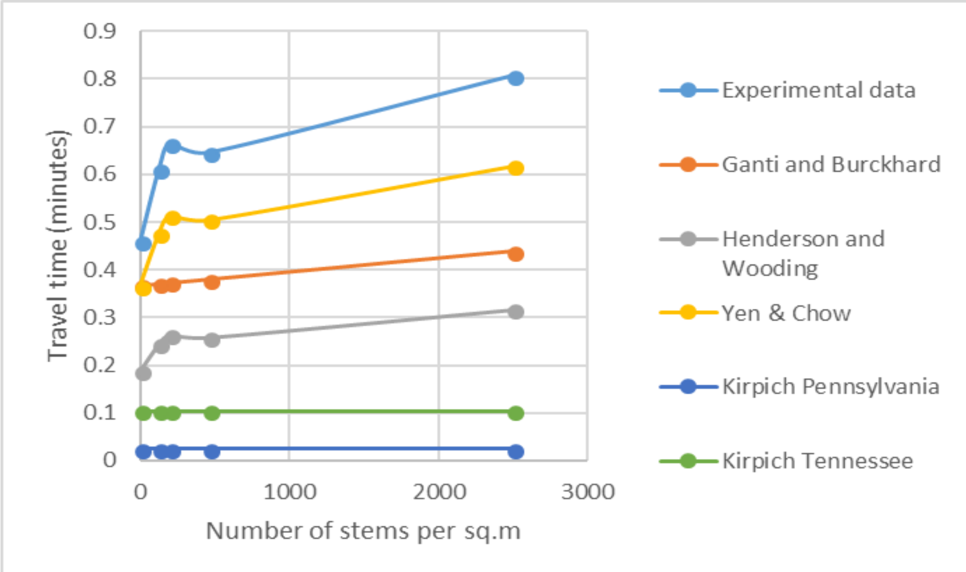

Figure 4.10 Model verification based on experimentally published results

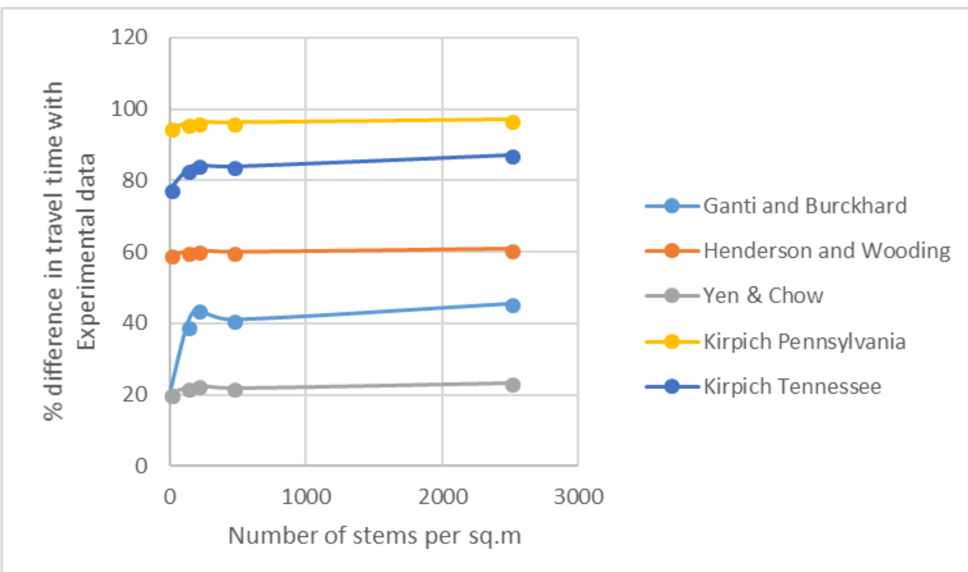

Figure 4.11 Variation in theoretically estimated and experimentally measured travel times

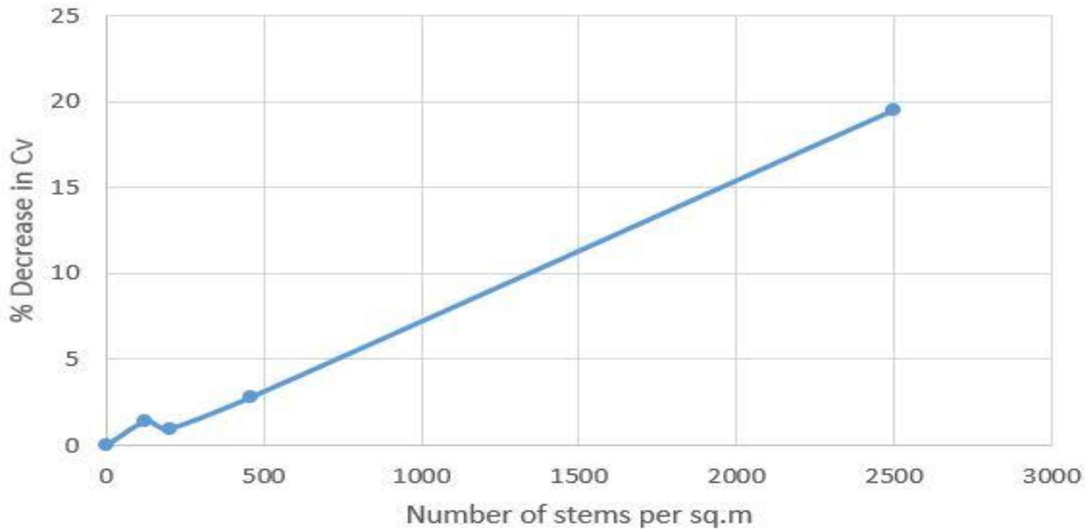

Figure 4.11 Effect of stem density in Chezy’s vegetation resistance coefficient

CHAPTER 5: CONCLUSION

The higher and lower estimation of travel time depends on selection of roughness parameter and its range of value. It is highly complex to replicate exact practical phenomenon in hydrology through any mathematical equation or experimental setup but at the end of the day better approximation in results matters for design purpose. From the Figure 4.4 overland flow shows it's mostly in laminar at bare soil and vegetation condition with slope of 8% during design storm intensities. The difference in estimated travel times based on Manning's velocity equation and Ganti and Burckhard equation is gradually increasing with stem density. Selecting any roughness coefficient value from the standard tables is going to give approximate result only when it is developed based on stem density. Standard tables of 'f_v' and 'C_v' for selected crops are developed based on $f_v = f_{b+}4C_d NDh$ in the present study for 25-yr design storm event. 'f_v' value increased with increase the crop residue and decreased with increase in slope. 'f_v' is a significant parameter in estimating flow depth, that flow depth is used to estimate 'C_v' which is main roughness parameter in travel time equation. So, the crop residue in watershed increases then 'f_v' increases which leads to decrease in 'C_v' hence travel time increases. The Ganti and Burckhard equation is validated based on published experimental data by Madi, Mouzai and Bouhadef then compared obtained results with experimentally measured travel time data and make a conclusion that mean flow velocity is reducing with increase in stem density resulting increase in overland flow travel time. Yen & Chow equation gives constant result for different rainfall intensities at same land cover which is not recommendable. The Ganti and Burckhard equation is based on stem density with homogeneous plants per square meter under rigid vegetation condition. Non-homogeneous plants stem density condition can be achieved partially by considering average value of plant cross-section.

CHAPTER 6: FUTURE RESEARCH

In order to obtain much more mathematical accuracy, dynamic wave equation for overland flow travel time should be developed for non-homogeneous plants per square meter under the flexible vegetation condition.

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