DISSERTATION

ESTIMATING OVERLAND FLOW SOIL TRANSPORT CAPACITY AND SURFACE EROSION RATE USING UNIT STREAM POWER

Submitted by:

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY HUI-MING SHIH ENTITLED ESTIMATING OVERLAND FLOW SOIL TRANSPORT CAPACITY AND SURFACE EROSION RATE USING UNIT STREAM POWER BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

ESTIMATING OVERLAND FLOW SOIL TRANSPORT CAPACITY AND SURFACE EROSION RATE USING UNIT STREAM POWER

The unit stream power was used to develop a physically-based model to estimate overland flow soil transport capacities and corresponding surface erosion rates in the study. This model considers the impact that physical factors have on computed overland soil transport capacities including varying hydraulic conditions and a maximum sediment concentration limit. This new soil transport capacity relationship, which is developed in this study, was incorporated in the CASC2D-SED watershed model. The revised CASC2D-SED model was applied to eight basins in three different watersheds to validate the overland flow soil transport capacity relationship and provide a practical tool for water and soil conservation management.

In past studies of event-based overland flow soil erosion, both empirical and physically-based approaches have been used to define soil transport capacity relationships and corresponding erosion rates. However, these previous relationships only provide a description of the factors that influence transport capacity based on site-specific data sets that considered only a limited range of conditions. In contrast, the overland soil transport capacity relationship developed as part of this study provides a more complete description of the factors that determine transport capacity.

A correlation analysis was used to determine the significant factors that impact transport capacity. The correlation analysis results show that unit stream power is the most dominant factor for soil transport. A bounded regression formula was used to reflect the limits that transported sediment concentrations cannot be less than zero or greater than a maximum value. The coefficients used in this new model were determined from nonlinear regressions using published experiment measurements. A one-dimensional overland flow diffusive wave model was used in conjunction with the new soil transport capacity equation to simulate field conditions and validate the model. The computed results were in good agreement with laboratory and field plot data.

To further validate the performance of the new overland soil transport equation and to provide a practical tool for watershed-scale application, the new equation was incorporated into a revised CASC2D-SED watershed model. Unlike the Kilinc-Richardson equation originally used in CASC2D-SED, the crop management factor (*C*) of Universal Soil Loss Equation is not required as a model input because unit stream power and other physical factors in the transport capacity equation can reflect the effects of dynamic flow resistance. Eight basins in three different watersheds were used to validate the revised CASC2D-SED model. Sensitivity analyses show that overland roughness using the Manning coefficient is more sensitive for sediment yield calculations than it is for hydrology simulations. By comparing with observed data, the variation range of predicted results is considered acceptable using the revised model.

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I would like to dedicate this dissertation to my family: my grandparents, my father and mother, my brother and sister, in-laws, as well as uncle Peter Chao. Lastly, I would like to say to all those whom I cannot specifically mention that your contributions will never be forgotten. To all of you, thank you.

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NOTATIONS

SYMBOLS		DEFINITION
A_s	=	contribution area per unit of contour length
A_w	=	watershed area in km^2
C_c	=	Courant number
c_d	=	diffusive wave celerity
CE	=	efficiency coefficient
c_k	=	kinematic wave celerity
C_{max}	=	maximum sediment concentration
C_{mgl}	=	sediment concentration in *mgl*
R	=	correlation coefficient
C_r	=	fraction of surface cover
C_s	=	sediment concentration, (q_s / q)
D_d	=	$\dfrac{Vh}{2S_f}$
D_d	=	drainage density in km^{-1}
d_s	=	particle diameter
D_s	=	particle deposition rate
d_{50}	=	mean particle size
d_*	=	dimensionless particle diameter
E_b	=	sediment bed load transport capacity
E_e	=	soil erosion rate by overland flow

SYMBOLS		DEFINITION
E_I	=	rainfall drop detachment rate
E_L	=	total sediment transport capacity of overland flow
E_p	=	sediment suspended load transport capacity
E_s	=	sheet flow sediment transport capacity
E_r	=	rill flow sediment transport capacity
f_i	=	soil infiltration rate
F	=	a coefficient based on cohesive particles
F_c	=	vegetative cover factor
f	=	Darcy-Weisbach friction factor
F_I	=	rainfall drops detachment impact factor
Fr	=	Froude number
F_1	=	area under reserved and protected forest in km^2
F_2	=	unclassified forest area in km^2
F_3	=	cultivated area in km^2
F_4	=	grass and pasture land in km^2
F_5	=	waste land in km^2
g	=	gravitational acceleration
G	=	specific gravity of sediment
h	=	flow depth
H	=	a coefficient based on sheet flow and rill flow
h_i^*	=	one-sided forward differences

SYMBOLS		DEFINITION
h_i^{**}	=	one-sided backward differences
i	=	rainfall intensity
i_e	=	excess rainfall depth
I_s	=	sediment transporting capacity index
I_Ω	=	Stream power index
j	=	simulation time
K_0	=	surface friction coefficient
K_s	=	representative soil erodibility factor
K'	=	dimensionless soil erodibility factor
L	=	runoff length
LS	=	USLE slope length and steepness factor
n_f	=	bed form roughness
n_c		Manning roughness coefficient for channel flow
n_d	=	relative roughness
n_i	=	rain drop disturbance roughness
n_L	=	land covers roughness
n_m	=	flow resistance from soil infiltration impact
n_o	=	Manning roughness coefficient for overland flow
n_s	=	flow lag roughness due to land cover interception
P	=	land practice factor
P_a	=	annual precipitation in cm
P_i	=	rainfall power

SYMBOLS		DEFINITION
q	=	unit discharge
Q_p	=	peak discharge
q_s	=	sediment discharge per unit width
qS	=	stream power per unit width
Q_v	=	storm runoff volume in acre-ft
R	=	USLE rainfall erosivity factor ($MJ \cdot mm/(ha \cdot h)$)
R_a	=	annual runoff in mm^2
Re	=	flow Reynolds number
Re_*	=	grain shear Reynolds number
Re_p	=	particle Reynolds number
r_s	=	specific weight of sediment
r_w	=	specific weight of water
R^2	=	squared correlation coefficient
S	=	bed slope
S_f	=	energy slope
S_{E_t}	=	gross amount of soil erosion (t/ha) using USLE
S_w	=	water surface slope
S_Y	=	event sediment yield
S_Ω	=	ratio of slope exponent to unit discharge exponent
t	=	time
T_c	=	overland flow transport capacity

SYMBOLS		DEFINITION
t_{ci}	=	runoff concentration time
ν	=	kinematic viscosity of water
V	=	flow velocity
V_{cr}	=	critical velocity required at incipient motion
V_i	=	rainfall velocity
VS	=	unit stream power per unit weight of water
V_{SAB}	=	sediment yield in $mm^3 year^{-1}$
W_i	=	Wetness index
x	=	distance
X_i	=	independent variables
X_{mean}	=	mean of a set of observed values
X_{obs}	=	observed value
X_p	=	p-predictor variable
X_{pred}	=	predicted value
Y	=	Shield parameter
$\hat{Y}$	=	dependent variable
Y_c	=	critical Shields parameter
Δt	=	time step
Δx	=	distance step
η	=	5/3 for turbulent flow
ρ	=	density of water

SYMBOLS		DEFINITION
ρ_s	=	density of sediment
θ	=	hill slope angle
θ	=	slope angle
ϕ	=	stream power per unit width in mass ($\phi = \rho g q S$)
ϕ_c	=	critical stream power
ϕ_e	=	effective stream power
τ	=	shear stress
τ_c	=	critical bed shear stress at the beginning of motion
μ	=	dynamic viscosity
u_*	=	shear velocity
ω	=	fall velocity
Ω	=	dominate variable
Ω_e	=	effective dominant variable
Φ	=	VS
Ψ	=	stream power τV
A,B,X,Y,M,N	=	variables
$b_0,\ b_1,\ b_2 \dots\ b_p$	=	coefficients
$s,k,\gamma,\alpha,\beta,\varepsilon,\lambda,a,b,j,m_i,n_i,$ α_1 and α_2	=	coefficients

CHAPTER I INTRODUCTION

1.1 Overview

Erosion and sedimentation are natural processes in a watershed. Soil erosion from a watershed pollutes surface waters and often has undesirable effects, such as reduced cropland fertility and increased water treatment costs (Brigham et al. 2001; Sekhar and Rao 2002). Soil erosion caused by water flow is a complex problem. Running water on a hillslope can cause landslides, debris flow erosion, and surface soil erosion. Surface soil erosion is an integrated process of rainfall splash detachment, sheet flow erosion, inter-rill flow erosion and rill flow erosion. It occurs on upland catchments within a watershed and is considered as a non-point pollution source of environmental problems.

Applications of Digital Elevation Model (DEM), Geographic Information System (GIS), and spatially distributed hydrologic models are commonly developed to predict the excess flow and sediment transport processes in a watershed. Because of the differences in hydraulic mechanisms between channel flow and overland flow (Govers 1992), spatial elements are divided into channel elements and overland flow elements in a distributed hydrologic model. In a distributed model, overland flow routing is treated as sheet flow. To estimate surface soil erosion rate is a complicated problem affected by micro-topography, land cover, surface materials, flow characteristics, boundary conditions, etc. Calculations of each overland flow element contain much information. It is difficult to have an analytical solution for the prediction of soil erosion processes. Therefore, empirical approaches using physically based parameters should be used to estimate sheet flow based surface erosion rate.

Both empirical and physically based approaches were used for the estimation of surface erosion rates and have presented different significant parameter groups in their soil erosion equations. Many of them can only be applied to a particular flow type, and may not be suitable for DEM based spatially distributed hydrologic models. Power function based equations were used in empirical approaches to represent sediment transport capacity. Their applicability is mainly limited to specific erosion patterns or laboratory studies. Because of using empirical approaches, there is a need to gather experimental data from previous studies to increase the statistical significance and build a physically based model for surface soil erosion research. In addition, many empirical models require a resistance factor to reduce the predicted soil erosion rate because their variables do not reflect the change of hydraulic resistance. Therefore, using physical factors to compute overland flow erosion rate can express the affects of hydraulic resistance.

Many previous studies recommended that the traditional form of bed material load transport equations for channel flow can be revised for overland flow soil erosion calculations. Using the unit stream power shows a physically strong ability to estimate sediment transport capacity. It provides a good physical foundation to develop an empirical overland flow erosion model by using laboratory, field plots, and experimental watershed data.

Generally speaking, the overland slope is steeper than the channel bed, and sediment concentration of overland flow is higher than that of channel flow. However, many existing sediment transport equations explain the increasing tendency of sediment concentration is the same as increasing flow discharge and slope. They might over-estimate sediment transport capacity at high sediment concentration. For overland flow, there should be a maximum concentration limit to compute sediment transport capacity.

The existing contributed hydrology model, CASC2D-SED (Julien and Rojas, 2002), has been used for hydrologic simulations. Its program codes are public domain and have been improved by extending more hydrologic calculations. CASC2D-SED codes can be revised to couple with the soil erosion model developed in this study. The experimental watershed data are used to validate the revised model and prove the application using the revised model.

The objectives of this study are to: (a) use the unit stream power to compute overland flow soil transport capacity and erosion rate from soil surface, (b) consider the maximum sediment concentration limit of overland flow in the equation developed in this study, and (c) validate the soil transport capacity equation for field plots by using a one dimensional diffusive model, and for experimental watersheds by using a revised CASC2D-SED model developed in this study.

1.2 Study Methodology

Soil erosion caused by running water is a complicated problem. The focus of this study is to evaluate surface soil transport and yield from the watershed upland using the unit stream power. Because soil erosion can be caused by many agents, the soil erosion estimation in this study is limited to event based storms, excluding extreme rainfall, and overland flow is the only agent for erosion. The erosive materials composed of sand, silt, and clay are transported by overland flow. The conditions of uniform sheet flow and flow equilibrium states are assumed for both hydrologic and sediment transport simulations in this study. The study objectives and methodology are described herein.

Relevant previous studies regarding sediment transport, soil erosion, pedology, water and soil conservation, watershed hydrologic modeling, overland flow hydraulics, watershed morphology and Geographic Information System (GIS) application were reviewed to understand overland flow characteristics of runoff hydraulics and surface soil erosion mechanics under a storm event.

The agreements of using the unit stream power to estimate overland flow soil erosion is explored and demonstrated by comparison between empirical models and theoretical approach using flow unit stream power and flow resistance equations. The published data are also used to verify the correlation between unit stream power and overland flow erosion rate. For statistical correlation and regression analyses, laboratory data published by Kilinc (1972), Aziz and Scott (1989), and Guy and Dickinson (1990) were used to verify important physical factors which significantly impact the overland flow soil erosion. These data include sheet flow and rill flow erosion, as well as rainfall simulation.

A bounded regression formula is used to develop the overland flow soil erosion equations with important physical factors and reflect the limits that sediment concentration cannot be less than zero nor greater than a maximum value. A sensitivity analysis is performed to test the parameters of the developed equations.

For practical applications of the developed equations, a dimensionless soil erodibility factor is used to reflect the soil erodibility. Existing distributed hydrologic models include overland flow routing and channel flow routing. In order to exclude open channel routing, a 1-D diffusive wave routing is developed to validate the overland flow sediment transport equation developed in this study. The second-order numerical method of the MacCormack scheme (MacCormack, 1971) is used for diffusive wave routing. The simulation results are compared with experimental field data by Barfield et al. (1983).

The overland flow sediment transport model developed in this study was applied to a spatially distributed hydrologic model based on CASC2D-SED. The revised model performance was demonstrated through case study applications to the Goodwin Creek watershed in Mississippi and Watersheds W2 and W3 in Iowa of the U.S. Department of Agriculture Research Service (USDA-ARS) in Iowa.

1.3 Expected Contributions

Expected contributions of this study are described below.

1. Estimating overland flow soil erosion capacity using the unit stream power is the

primary contribution from this study.

2. The statistical and physical characteristics of overland flow experimental data are used to verify flow unit stream power as a dominant variable, and to determine important physical factors. Correlation and regression analyses are used to indicate that parameters are consistently significant for the published experimental data used in this study.

3. A bounded function based regression formula is used to develop the overland flow sediment transport equations with verified significant factors. The equations thus developed can predict sediment transport rate with varying flow conditions and rainfall impact. They also have to include the considerations of sediment concentration limits which are excluded in most existing overland flow erosion models.

4. An overland flow erosion model based on the unit stream power is developed and used to revise the CAS2D-SED model. The predicted soil erosion rate using the developed soil erosion model is adjusted by changing physical variable values. Without using the crop management factor *C*, the revised CAS2D-SED model can predict overland flow erosion rate with significant physical variables, and also consider the rainfall enhancement of soil erosion.

5. The study results can provide the following useful information: (1) Identify high erosion areas; (2) Set priority for erosion protection; and (3) Use as a management tool for water and soil conservation practices.

This study will also provide a sound foundation for developing a more general and more universally applicable soil erosion model. This model should also provide a useful means to organize field observations and to identify data gaps for the design of future studies to improve estimates of the spatially distributed hydrologic parameters.

CHAPTER II LITERATURE REVIEW

This study reviewed relevant literature and studies over a period of more than 70 years (1936~2007). The subjects cover watershed hydrology, non-point source pollution of soil erosion, overland flow characteristics, surface soil properties, sediment transport, spatially distributed hydrology, soil erosion models, and geographic information system (GIS). They are briefly described in the following sections.

2.1 Soil Erosion Pollution

Erosion and sedimentation are natural processes in a watershed. Excessive erosion can be caused by poor land use and poor land management practices adopted within the watershed. For example, uncontrolled deforestation due to forest fires, grazing, incorrect methods of tillage and unscientific agricultural practices are some of the bad land management practices. They can result in a large increase of sediment inflow to streams. In addition, upland erosion pollutes surface waters and often causes serious problems when deposition occurs (Frenette and Julien, 1987). Soil erosion in catchment areas and its subsequent deposition in rivers, lakes and reservoirs is one of the greatest concerns for two reasons (Sekhar and Rao, 2002). First, rich fertile soil is eroded from the catchment areas, reducing them to poverty. Secondly, sediment will cause the loss of reservoir capacity and degrade downstream water quality. Brigham et al. (2001) studied the damages of upland soil erosion of the Red River in Minnesota.

According to their study, soil erosion may reduce the fertility of cropland. Agricultural drainage ditches filled with eroded sediment over time may require costly maintenance. In their report, water utilities that use water from the Red River of the north as a source of drinking water must spend a significant amount of money to treat water with a high sediment concentration. Lake Winnipeg receives most of its tributary sediment loading from the Red River. High suspended-sediment concentrations can also adversely affect aquatic ecosystems of Lake Winnipeg (Waters, 1995). Meyer and Perry (1979) stated that soil erosion from upland area is a major source of river sediment. For non-point source pollution in a watershed, sediment and nutrients are major environmental concerns.

The Global Assessment of Human Induced Soil Degradation (GLASOD) (International Soil Reference and Information Centre, 2007) study estimated that about 15 percent of the Earth's ice-free land surface is afflicted by all forms of land degradation. Accelerated soil erosion by water is responsible for about 56 percent and wind erosion is responsible for about 28 percent (Oldeman, 1991). Fig. 2.1 shows the soil degradation distribution in the world. Soil erosion pollution also causes economic loss in countries. For example, soil erosion cost in the United States is estimated to be between US$30 billion (Uri and Lewis, 1998) and US$44 billion (Pimental et al., 1993) annually. The annual cost in the United Kingdom is estimated at £90 million (Environment Agency, 2002). Soil erosion studies can help people understand soil loss mechanisms as well as improve land loss protection.

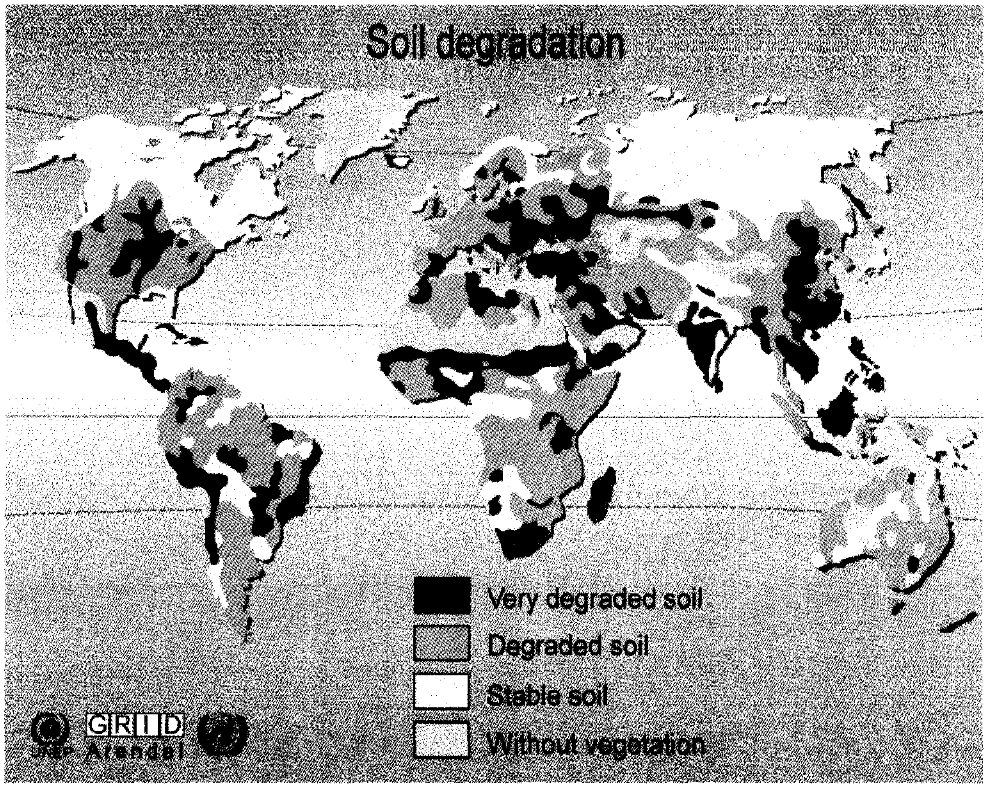


Figure 2.1. Soil degradation map of the world.

2.2 Hillslope Soil Erosion Types

Running water, wind and human activities are three causes of soil erosion. Erosion caused by running water is a concern during storms, which is the focus of this study. Because of gravity and running water, soil erosion from landslide, mudflow or debris flow, and surface erosion may occur during storm events. They are defined as

Landslide: Masses of rock, earth, or debris move down a slope (Federal Emergency Management Agency, 2006). Landslides can create large crevasses, change the course of streams and rivers, and cause flash floods.

Mudflow: Mudflow or debris flow is like a river of flowing rock, earth, and other debris saturated with water (FEMA 2006). It develops when water rapidly accumulates in the ground, during heavy rainfall or rapid snowmelt, changing the earth into a flowing river of mud. They can flow rapidly, striking with little or no warning at avalanche speeds. They also can travel several miles from their source, growing in size as they pick up trees, boulders, cars, and other materials. Their sediment concentration is about 45%~55% by volume (O'Brien, 2006).

Surface erosion: Individual soil particles are detached by rain drops or surface flow from soil mass and transported down slope by surface flow.

Landslide and mudflow are usually generated by heavy rainfall or extreme rainfall events and may cause locally heavy soil loss in the short term. Surface soil erosion is the primary objective of long term observation of watershed soil loss and is studied in this research. Surface erosion caused by water can be classified into three types, splash erosion, sheet/interrill erosion, and rill erosion. The definitions of these erosion types are described as below (Gregory, 1982).

1. Splash Erosion: When a rain drop impacts the soil, its kinetic energy is dissipated on the soil and the soil particles are first detached and then tossed, or transported, to a new location.

2. Sheet/Interrill Erosion: Sheet erosion is the uniform removal of soil in thin layers from sloping land, resulting from sheet or overland flow. Splash and sheet erosion are usually combined and called interrill erosion.

3. Rill Erosion: When runoff begins to form small concentrated channels, rill erosion occurs where soil is detached and transported by a concentrated flow of

water. Rill patterns are not always continuous paths in the field and can easily reform due to flow, land cover, soil type, or land use changes. The rill density and pattern cannot be easily determined in practice.

In the field, sediment transport efficiency of sheet/interrill flow is higher than rill flow. Rills transport flow and sediment which are contributed by upstream flow and lateral sheet/interrill flow. The transport capacity of rill flow is 85% attributable to sheet/interrill flow, and only 15% attributable to the rill flow (Guy et al., 1992). The rill flow impacts on overland flow erosion can be neglected at steep slopes and high rainfall intensity (Yang, 1996b).

2.3 Eroded Soils

Most soil eroded by surface flow is composed of sand, silt and clay (Leopold et al., 1964; Foster et al., 1981). Depending on depth, color, texture and chemical composition, soil can be divided into classes. Excluding organic matter, the United States Department of Agriculture (USDA) provides a soil textural map (Fig. 2.2) (USDA, 1993) to classify soil types. Soils are formed in layers called horizons. The capital letters, O, A, B, C, and E, are used to identify the master horizons (Fig. 2.3). Most soils have three major horizons, the topsoil (A), the subsoil (B), and the substratum (C). Some soils have an organic horizon (O) on the surface. Because of different soil textures, earth compaction and organic matter, the soil erodibility decreases from the surface soil to deep soil layers. Erodibility is the inherent susceptibility of soil particles or aggregates to become detached or transported by erosive agents such as rainfall and surface runoff. Erodibility is dominated by soil properties, land cover and topography. During a storm event, topsoil is the first and primary eroded layer. Its thickness varies with location. Usually, it is about three inches at the hilltop and deeper than five inches near channels (Ferris, 1996). Over 50 % of topsoil thickness is deeper than six inches.

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) uses an erodibility factor (*K*) to represent the soil erodibility. The erodibility factor physically expresses soil characteristics. It is applied to existing soil erosion models such as the Agricultural Non-point Source Model (AGNPS) (Bragadin et al., 1993), USDA Water Erosion Prediction Project (WEPP)(Foster and Lane, 1987), Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Foster et al., 1980) and CASCade Two Dimensional SEDiment (CASC2D-SED) (Johnson et al., 2000).

Foster et al. (1981) expressed soil erodibility based on soil structure, permeability, and percentages of sand and organic matter. Fig. 2.4 is provided by the USDA to estimate the soil erodibility factor (*K*). Eq. (2.1) can be used to determine the soil erodibility factor (Foster et al., 1981).

$$K = \frac{2.1P^{1.14} \cdot 10^{-4} \cdot (12-a) + 3.25(b-2) + 2.5(c-3)}{100} \tag{2.1}$$

where P = (silt % + very fine sand %) (100%- clay %); a = % of organic matter; b = structure code; and c = permeability class. The soil texture map (Fig. 2.2) can be used to determine soil erodibility factors for a particular soil type. The USDA provides a national database of soil erodibility factors for soil erosion applications.

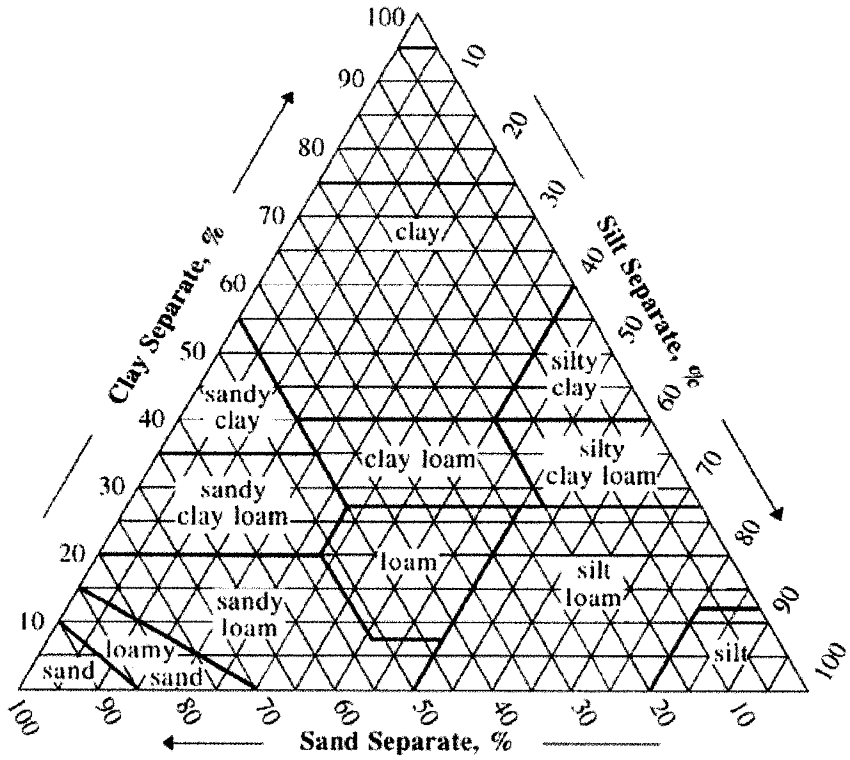


Figure 2.2. The USDA Soil Textural Triangle (USDA, 1993)

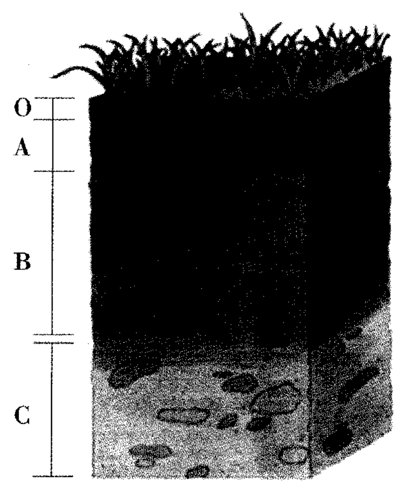


Figure 2.3. Soil horizons profile (Natural Resources Conservation Service, 2007)

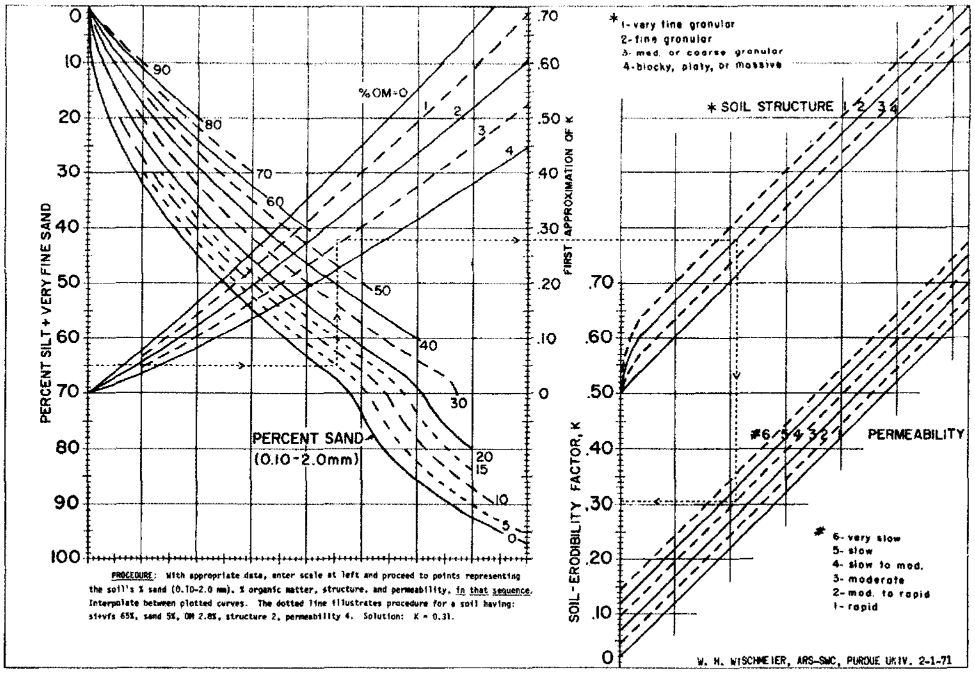


Figure 2.4. USDA nomograph used to calculate soil erodibility (K) factor

2.4 Surface Water Erosion Capacity Equations

2.4.1 Impact factors of surface soil erosion

Soil erosion or yield on soil surface can be expressed as a function such as (Wischmeier and Simith, 1978)

$$\text{Soil Yield} = f(\text{Erosivity}, \text{Erodibility}) \qquad (2.2)$$

Erosivity is the soil loss potential caused by overland flow and rain drop detachment. It is a function of overland flow characteristics, bed conditions and rainfall intensity. Erodibility is the inherent susceptibility of soil particles or aggregates to become detached or transported by erosive agents such as rainfall and surface runoff. Erodibility is dominated by soil properties, land covers and topography. Section 2.3 states that an erodibility factor (K) is widely applied in soil erosion models to estimate the sediment transport capacity of different bed materials.

For event based soil erosion modeling, Moss (1979) stated that the basic mechanisms of erosion, transportation and deposition vary little from rivers to overland flow. Ferro (1998) verified the applicability of fluvial sediment transport formulas to overland flow. Their findings demonstrated that the existing overland soil erosion models were mostly revised from fluvial sediment transport formulas. Including the factors used in fluvial sediment transport equations and overland flow characteristics, the important variables commonly used in erosion equations are listed below.

Julien and Frenette (1985)-

$$q_s = f(h, V, i, q, L, \tau, \tau_c, S, \rho, v, d_s, \rho_s) \qquad (2.3)$$

Govers (1985)-

$$q_s = f(u_*, \Phi, S, q, \mathit{Land\ cover}) \qquad (2.4)$$

Moore and Burch (1986)-

$$q_s = f(V, S, \tau, q) \qquad (2.5)$$

Low (1989)-

$$q_s = f(\Psi, S, r_w, \mathit{Shield\ parameter,\ Sediment}) \qquad (2.6)$$

$$\text{Shield parameter} = f(\tau, r_s, r_w, d) \qquad (2.7)$$

where τ_c = the critical bed shear stress at the beginning of motion; v = the kinematic viscosity of water; V = the average flow velocity; h = flow depth; i = rainfall intensity; q = discharge ($q = Vh$); S = slope; ρ and ρ_s = density of water and sediment; r_w and r_s = specific weight of water and sediment; d_s = particle size; L = runoff length; τ = bottom shear stress; u_* = shear velocity; Φ = unit stream power; and Ψ = stream power.

Unit stream power Φ is defined as the rate of potential energy dissipation per unit weight of water (Yang, 1972, 1976, 1996a). Its definition is

$$\Phi = \frac{dY}{dt} \tag{2.8}$$

where Y = potential energy per unit weight of water; and t = time. If flow is mainly dominated by gravity force, and the energy dissipation caused by sediment transport can be ignored, unit stream power can be represented by the product of flow velocity and energy slope along the primary flow direction. Then, unit stream power can be simply defined as (Yang, 1972)

$$\Phi = \frac{dY}{dt} = \frac{dx}{dt}\frac{dY}{dx} = VS_f \tag{2.9}$$

where x = distance; V = flow velocity along primary direction, and S_f = energy slope.

For overland flow, stream power per unit bed area can be expressed as

$$\Psi = \tau V = \gamma_w \cdot h \cdot S_f \cdot V = \gamma_w \cdot q \cdot S_f \tag{2.10}$$

Stream power per unit bed area τV and stream power per unit width qS_f have the same dimension for overland flow. When water specific weight γ_w is considered as a constant, stream power per unit width can be expressed by

$$\Psi \propto q \cdot S_f \tag{2.11}$$

Table 2.1 lists seven sediment transport models and their primary parameters. Those models are used to calculate sediment transport under precipitation events for small watersheds.

Table 2.1. Parameters considered in existing sediment transport models

	Rainfall drop impact	Particle fall velocity	Soil properties (Particle size, soil type)	Incipient motion	Land cover	Discharge	Shear stress	Stream power (τV)	Note
WESP (watershed erosion simulation program)	○	○	○			○	○		Small watershed
Paringit & Nadaoka (2003)	○	○	○		○	○	○		Small agricultural Catchment
HEM (Hillslope erosion model)			○		○	○			Entire burn area
Transport capacity equation (TCE) of WEPP	○		○	○		○	○		
Govers (1992)			○	○			○		
Ferro (1998)			○				○	○	
Yalin(1963)			○				○		

Hydraulic properties of channel flow are different from those of overland flow (Govers, 1992). Some of the factors for fluvial sediment transport calculation may not have significant impacts on overland flow. For empirical overland flow erosion equations, their application may be limited by their experiment scale and data range. Therefore, one of the primary objectives in this study is to determine which factors are significant for overland flow erosion.

2.4.2 Erosion model classification and formulas

Existing mathematical models for soil erosion can be divided into (Hrissanthou 2005)

(a) empirical concepts (e.g., Universal Soil Loss Equation, Wischmeier and Smith, 1978; Santos et al., 1997; Johnson et al., 2000)

(b) causal or fundamental concept (e.g. Hairsine and Rose, 1992a,b; Flanagan and Nearing, 1995; Morgan et al., 1998; Bathurst, 2002)

(c) the concept of unit sediment graph (e.g., Williams, 1978; Kumar and Rastogi, 1987; Das and Agarwal, 1990)

(d) stochastic concept (e.g., Smith et al., 1977; Moore, 1984)

Empirical models are simple, but they do not explain the mechanisms of the physical processes. In causal or fundamental models, the soil erosion is subdivided into different processes based on physical sub-processes and surface topography. They are represented by the following formulas.

Julien and Simons (1985)

$$E_L = E_s \cdot F_I \tag{2.12}$$

Foster and Meyer (1972), Guy et al (1990), and Silburn and Loch (1989)

$$E_L = E_s + E_r + E_I \tag{2.13}$$

Chen et al (2006)

$$E_L = E_b + E_p + E_I \tag{2.14}$$

where E_L = total sediment transport capacity of overland flow; F_I = raindrop detachment impact factor; E_s = sheet flow sediment transport capacity; E_r = rill flow sediment transport capacity; E_I = raindrop detachment rate; E_b = sediment bed load transport capacity; and E_p = sediment suspended load transport capacity. These models required numerous data for determination of the parameters in the corresponding equations. Therefore, they may have spatial scale limits on their application because large watersheds should be more complex compared to small basins.

The unit sediment graph and the unit hydrograph are system functions, and can be used to describe the sediment behavior of a basin. By means of stochastic models, sediment yield from a basin can be predicted as a function of rainfall or runoff. However, the mechanism of sediment production in the basin is not taken into consideration.

Because surface erosion involves many factors and is a complex problem, erosion equations and erosion indices are commonly used to predict the erosion potential of watersheds. Ferro (1998) listed several sediment transport equations and soil erosion indices to represent the spatial distribution of erosion potential within a watershed. This study reviews relevant empirical sediment transport equations and erosion indices. Table 2.2 presents some soil erosion equations and erosion indices applicable to a watershed.

Many of the existing hydraulic equations can be expressed by power functions. The power function type of models is often used to obtain a statistical solution. For the *p*-predictor variable (X_p), the power model takes the form (McCuen, 1992):

$$\hat{Y} = b_0 X_1^{b_1} X_2^{b_2} \cdots X_p^{b_p} \tag{2.15}$$

where $\hat{Y}$ = dependent variable, X_i = independent variables, and b_0, b_1, $b_2 \ldots$ b_p = coefficients. Because flow discharge and bed slope are traditionally considered as significant factors and can be directly measured in the laboratory, a commonly used empirical erosion equation is

$$q_s = \alpha S^{\beta} q^{\gamma} i^{s} \left(1 - \frac{\tau_c}{\tau}\right)^{\kappa} \tag{2.16}$$

where $\alpha, \beta, \gamma, \kappa$ and s = constant coefficients; and i = rainfall intensity (Julien and Simons, 1985). The term, $\left(1 - \frac{\tau_c}{\tau}\right)$, represents the resistance from incipient motion. For different flow types and bed materials, α is a function of flow resistance and soil erodibility (Julien and Simons 1985, and Sharma and Correia 1987).

When the rainfall impact and incipient motion criteria for particles are disregarded, Eq. (2.16) can be simplified as

$$q_s = \alpha S^{\beta} q^{\gamma} \tag{2.17}$$

The values of $1.2 < \gamma < 1.9$ and $1.4 < \beta < 2.4$ are recommended by Julien and Simons (1985). The values of $1.0 < \gamma < 1.8$ and $0.9 < \beta < 1.8$ are recommended by Prosser and Rustomji (2000). For overland flow, sediment transport rate is defined as the amount of soil particles carried by running water and expressed by a production of flow discharge and sediment concentration.

$$q_s = q \cdot C_s \tag{2.18}$$

Table 2.2. Empirical erosion equations and potential indices

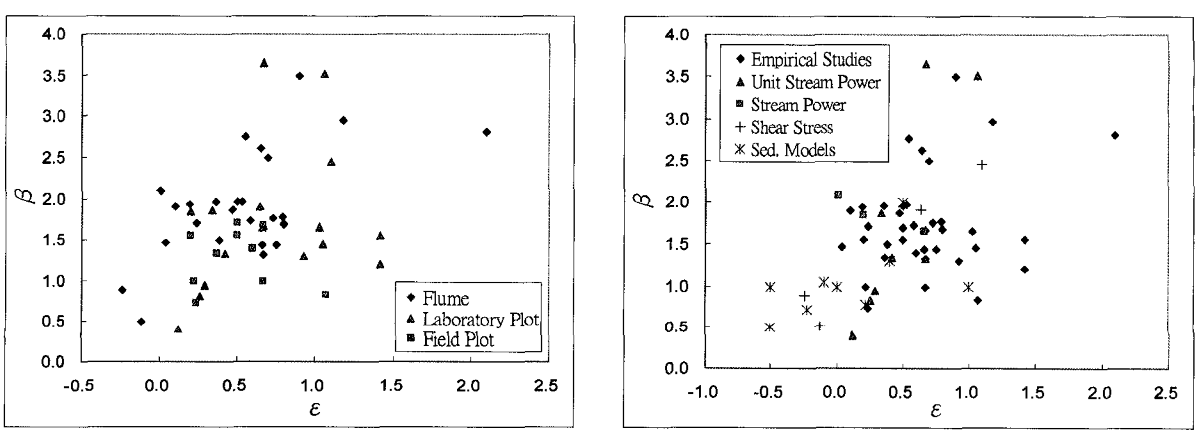
Investigator	Equation
Beven and Kirkby (1979) (Wetness index W_i)	$W_i = \ln \frac{A_s}{S}$
Moore and Wilson, (1992) Stream power index(I_Ω)	$I_\Omega = A_s \cdot S$
Moore and Wilson, (1992) Sediment transporting capacity index (I_s)	$I_S = \left[\frac{A_s}{22.13}\right]^{0.6} \left[\frac{S}{0.0896}\right]^{1.3}$
Desmet and Govers (1996)	$I_s = 4 \cdot k \cdot S^{1.4} \cdot A_s^{0.5}$
Vertessy et al., (1990) sediment transporting capacity index(I_s)	$I_s = \rho \cdot g \cdot A_s \cdot i_e \cdot S \cdot \alpha_1 \cdot e^{-\alpha_2 \cdot (1-C_r)}$
Aziz and Scott (1989) and Smart (1984)	$E_L = \frac{6.42 \frac{\rho_s}{\rho} \cdot S^{0.6}}{(\frac{\rho_s}{\rho} - 1)^{3/2}} (1 - \frac{\tau_c}{\tau}) \Psi$
Moore and Burch (1986)	$\log C_s = 5.0105 + 1.363 \cdot \log (\frac{\Phi - 0.002}{\omega})$
Hairsine and Rose (1992, a,b)	$\phi_e = HF(\phi - \phi_c)$
Barekyan (1962)	$q_s \sim SqV$
Yalin (1977)	$q_s \sim \tau_0^{0.5} (\tau_0 - \tau_c)^2$
Engelund-Hansen (1967)	$q_s \sim \tau_0^{1.5} V^2$
Kalinske-Brown (Julien and Frenette, 1985)	$q_s \sim \tau_0^{2.5}$
Shields (1936)	$q_s \sim Sq(\tau_0 - \tau_c)$
Low (1989)	$q_s = \frac{6.42 \frac{\rho_s}{\rho}}{(\frac{\rho_s}{\rho} - 1)^{1/2}} \frac{(Y - Y_c)}{S^{0.4}} \frac{h}{d_s} \Psi$

Note: A_s = contribution area per unit of contour length; k = a proportionality factor; i_e = rainfall excess rate; α_1 and α_2 = constants depending on soil type and surface management; $(1 - C_r)$ = the fraction of surface cover in contact with the ground; H = a coefficient based on sheet flow and rill flow; F = a coefficient based on cohesive particles; ϕ = stream power per unit width in mass ($\phi = \rho g q S$); ϕ_c = the critical stream power; ϕ_e = effective stream power; E_L = overland flow transport capacity; ω = fall velocity, and Y and Y_c = Shields parameter and critical Shields parameter, respectively.

Eq. (2.18) can be re-written as

$$C_s = \alpha S^{\beta} q^{\varepsilon} \tag{2.19}$$

where $C_s = q_s / q$; and $\varepsilon = \gamma - 1$. Because sediment concentration is proportional to slope and flow discharge, the coefficients, β and ε, should be greater than zero. Table A.1 (Appendix A) lists the values of exponents in Eq. 2.19 of existing overland flow sediment transport equations from 1947 to 1999. We can see that some equations have negative power coefficients for unit flow discharge. This means that some of the sediment concentration is inversely proportional to unit discharge, which is not reasonable. Fig. 2.5 shows that exponents in Eq. 2.19 are not constant and they vary with different data sources and applied factors. It might over-estimate sediment concentration using large exponent values and under-estimate sediment concentration using small exponent values. Results in Fig. 2.5 imply that Eq. (2.19) should consider the variation of flow conditions.



a b

Figure 2.5. Exponents of the sediment transport equations for overland flow

The correlation coefficient measures the strength of a linear relationship between two variables. The Pearson correlation method (McCuen, 1992) is used to determine the correlation coefficient R between β and ε values of empirical models. The correlation coefficient is defined as

$$R = \frac{\sum (X - \overline{X})(Y - \overline{Y})}{\sqrt{\sum (X - \overline{X})^2 \sum (Y - \overline{Y})^2}} \tag{2.20}$$

Where X and Y = sample values; and $\overline{X}$ and $\overline{Y}$ = average values of samples X and Y.

The correlation coefficient is always between -1 and +1. The closer the correlation is to +/-1, the closer to a perfect linear relationship. Several authors have offered guidelines for the interpretation of a correlation coefficient. The suggested interpretations for correlations are illustrated as below (Cohen, 1988).

- -1.0 to -0.7 : strong negative association.
- -0.7 to -0.3 : weak negative association.
- -0.3 to +0.3 : little or no association.
- +0.3 to +0.7 : weak positive association.
- +0.7 to +1.0 : strong positive association.

Fig. 2.6 presents the relationships between β and ε values of empirical models. The correlation coefficient R is 0.25 and explains that β and ε can be considered as independent with each other. Each pair of β and ε represents a certain flow condition. By varying the values of β and ε, Eq. 2.19 indicates flow sediment transport capacity for different flow conditions.

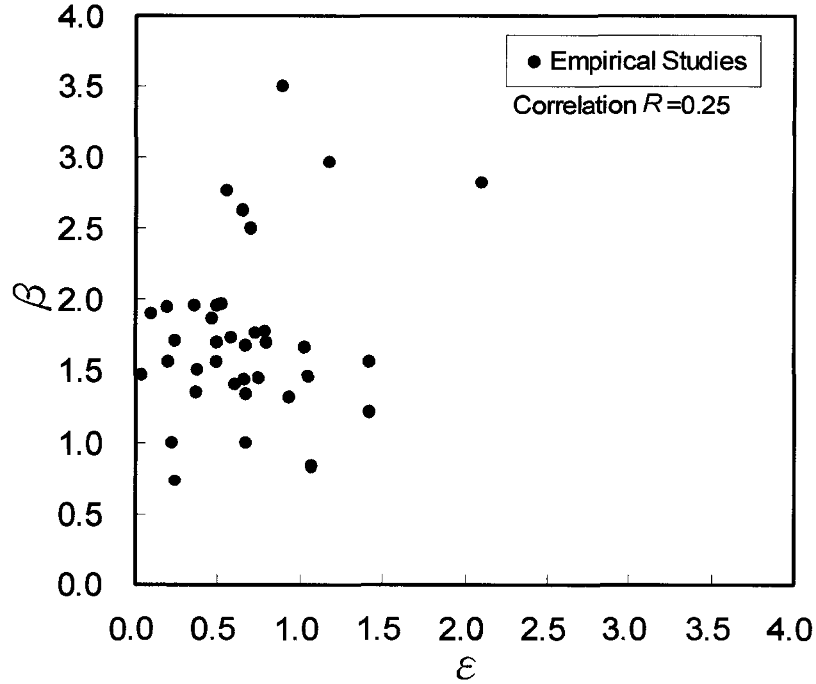


Figure 2.6. Relationships between exponents β and ε of empirical studies in Eq. 2.19.

2.4.3 Maximum sediment concentration limit

Single sand particles have an average density of 2.65. When water or air fills in pores and effects from external forces such as packing and ramming, clusters of sand particles can have different densities. For overland flow erosion, sediment particles are only carried by water. Excluding external packing, the maximum density occurs when the pores between particles are filled by water (Fig. 2.7). Therefore, the maximum density of wet sand is 1.922, which has a porosity of 41% by volume (Rawls and Brakensiek, 1983). A sediment concentration of 1922,000 *mgl* is used as the maximum concentration of sand particles.

Figure 2.7. Flow discharge and sediment concentration tendency

Because most equations were developed from limited data, their coefficients are treated as constant values and statically fitted to sample data. When the power coefficients are constant, the sediment transport rate is proportional to the flow discharge rate and bed slope. There should be an allowable maximum sediment concentration for bed materials transported by flow. Fig. 2.8 shows that the increasing tendency of sediment concentration is not the same as increasing flow discharge and bed slope.

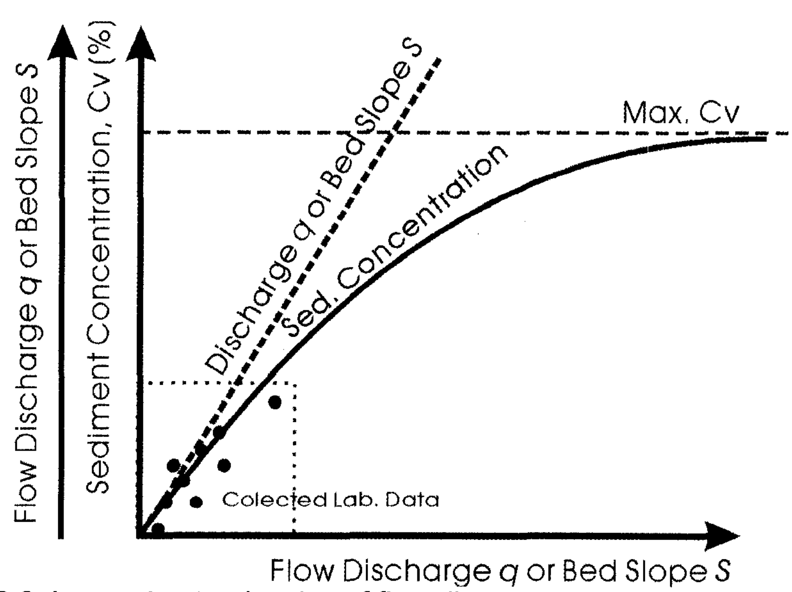


Figure 2.8. Increasing tendencies of flow discharge, bed slope, and sediment concentration

Eq. (2.19) may over-estimate sediment concentration at high flow rates or steep slope conditions because it does not have an upper limit of sediment discharge. For example, two overland flow sediment transport equations are expressed as

Kilinc's (1972)-

$$C_{mgl} = 1986289351 \cdot q^{1.035} S^{1.664} \tag{2.21}$$

Guy et al (1987)-

$$C_{mgl} = 1.13 \cdot 10^{18} \cdot q^{2.986} S^{8.835+0.767\ln(q)} \tag{2.22}$$

where C_{mgl} =sediment concentration in *mgl*. As flow discharge increases, the predicted sediment concentrations may exceed the maximum concentration limit. Fig. 2.9 and Fig. 2.10 show the over-estimation of sediment concentration using Eqs. (2.21) and (2.22). Therefore, the power coefficient for flow rate in sediment transport equations should not be a constant. A rational sediment transport equation for overland flow erosion should consider the maximum sediment concentration limit.

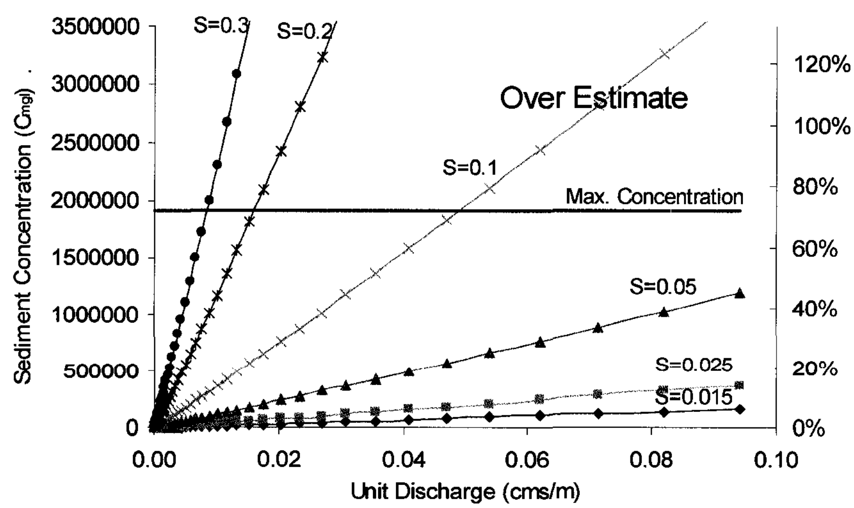


Figure 2.9. Kilinc's (1972) sediment transport equation for overland flow

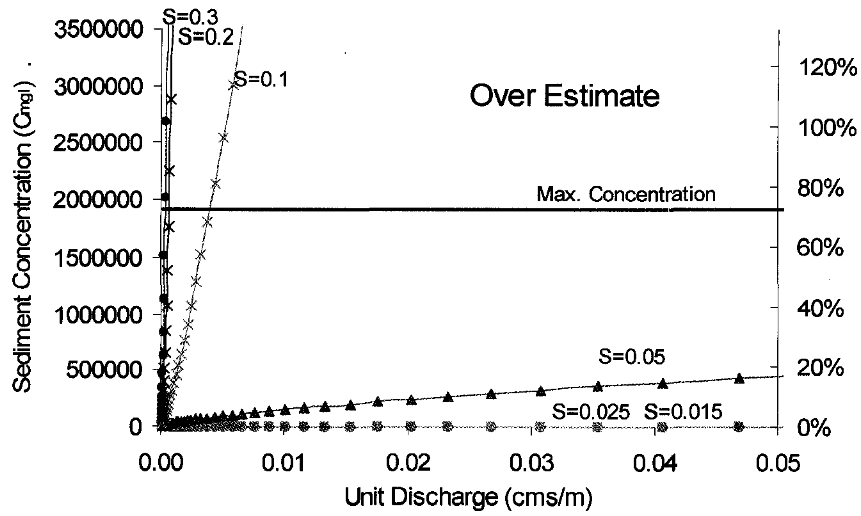


Figure 2.10. Guy et al. (1987) sediment transport equation for overland flow

Unit stream power theory can be applied with accuracy to estimate sediment transport for alluvial channels, and it is also recommended for overland flow sediment transport study. Based on unit stream power, Govers and Rauws (1986) found that a semi-empirical formula to fit their data is

$$q_s = A \cdot VS + B \tag{2.23}$$

where A and B = coefficients; and VS = unit stream power Φ.

Hairsine and Rose (1992 a,b) and Moore and Burch (1986) expressed surface erosion using Yang's (1973) sediment transport formula as

$$\log C_s = X + Y \log(\frac{\Phi - V_{cr} S}{\omega}) \tag{2.24}$$

where C_s = sediment concentration; ω = fall velocity; X and Y = dimensionless parameters reflecting flow and sediment characteristics; Φ = unit stream power; S = energy or water surface slope of the flow; and V_{cr} = critical velocity required at incipient motion.

Moore and Burch (1986) have shown that Eq. (2.23) is applicable to sheet and rill erosion with

$$X = 5.0105 \pm 0.0443 \tag{2.25}$$

$$Y = 1.363 \pm 0.030 \tag{2.26}$$

For sheet and rill flows with very shallow depth, Moore and Burch (1986) found that the critical unit stream power required at incipient motion can be approximated by a constant:

$$\frac{V_{cr}S}{v} = 4105\ \text{m}^{-1} \tag{2.27}$$

$$\text{or}\ \ V_{cr}S = 0.002\ \ \text{m/s} \tag{2.28}$$

where v = kinematic viscosity of water. Combining Eq. (2.24) through Eq. (2.28)

$$\log C_s = 5.0105 + 1.363 \cdot \log\left(\frac{\Phi - 0.002}{\omega}\right) \tag{2.29}$$

The accuracy of Eq. (2.29) was verified by laboratory data (Moore and Burch, 1986). Factors affecting overland sediment transport capacity depend not only on Φ and ω but also on rain fall impact, land cover, soil properties, water depth, etc. Therefore, in this study, we will gather more surface soil erosion data, to derive rational power function regression equations.

According to Gover and Rauws (1986) observations, sediment concentration on a plane bed is related to the shear velocity of the flow. Gover's observation is contrary to Rauws (1984) data, where there is no good correlation between the transported sediment concentration and total shear velocity for flows on an irregular bed. Therefore, this study will review and clarify those dominant factors suggested by previous studies.

2.5 Rainfall Impact and Spatial Distribution

Raindrops and their spatial distribution are important subjects in hydrologic studies. For overland flow, raindrops would disturb flow, increase flow resistance and detach soil particles from the surface. A physically based sediment transport model for overland flow erosion should consider raindrop impacts. For long term soil loss calculation, the USLE model uses a rainfall erosivity factor, R, to represent the annual water input in a watershed. For a rainfall event, Foster and Meyer (1972), Guy et al. (1987), Silburn and Loch (1989), and Chen et al. (2006) calculated soil particle detachment due to raindrop impacts with individually added terms in their equations. The formulas are shown in Eq. (2.13) and Eq. (2.14). However, raindrop not only cause soil particle detachment but also impact the sediment transport capacity of overland flow. Therefore, a sediment transport equation for overland flow should have a term for rainfall impact.

For laminar flow, Julien and Simons (1985) showed the rainfall impact on flow resistance by incorporating it into the Darcy-Weisbach friction factor f as:

$$f = \frac{K_t}{\mathrm{Re}} = \frac{\left(K_0 + Ai^b\right)\cdot V}{\nu D} \tag{2.30}$$

where K_t = friction factor including both effects that are due to surface roughness and rainfall intensity; Re = Reynolds number; K_0 = surface friction coefficient; A and b = empirical coefficients; V = overland flow velocity; D = water depth; i =rainfall intensity; and ν = kinematic viscosity. Eq. (2.30) shows that flow resistance can be increased by raindrops.

Rainfall intensity may not fully represent the rainfall impact for sediment transport. Other studies used rainfall velocity and rainfall power to represent the rainfall impacts on overland flow, and these physical factors are expressed as

$$V_i = 6.6 i^{0.07} \quad \text{(Schmidt, 1993)} \qquad (2.31)$$

$$P_i = \frac{\rho i V_i^2 \cos\theta}{2} \quad \text{(Gabet and Dunne, 2003)} \qquad (2.32)$$

where V_i = raindrop velocity; P_i = rainfall power; ρ = density of water (1000 kg/m^3); and θ = hill slope angle.

Ferro (1998) suggested that rainfall influence on overland flow can be ignored when

Bed Slope > 9%

Rain intensity < 50mm/hr

Water Depth > 3 rain drop diameter

He expressed the relationships among bed slope, rainfall intensity, and water depth as factors for rainfall impact consideration. In this study, rainfall intensity, raindrop velocity, rainfall power, etc. were used to clarify the rainfall influence of overland flow erosion.

2.6 Distributed Hydrology Models

2.6.1 Applications of distributed hydrology models

Due to the empirical nature and other limitations of empirically based models, physics-based distributed models have been developed for different reasons. The physically based models try to reflect precipitation distribution, simulate event storm hydrograph, assess and manage non-point source pollution, explicitly model soil erosion processes, model drainage basin evolution, and to apply at a variety of spatial and temporal scales with varying degrees of success.

The use of distributed hydrologic models has gained acceptance over lumped models because of their ability to handle spatial variation of both climatic and topographic parameters (Kalin et al., 2003). Diffusive wave routing was applied in hydrologic models for calculating flow velocity and discharge (Johnson et al., 2000; Orlandini and Rosso, 1996).

During a precipitation event, only the saturated area of a watershed can contribute runoff to the channel network. This can result from excess rainfall and runoff from saturated soil. The topographic model (TOP model) of Beven and Kirkby (1979) used a topographic index for the location and extent of the saturated contribution area. For study of overland flow erosion, soil particles are carried by running flow within the saturated contribution area.

Through applications of Digital Elevation Model (DEM), Geographic Information System (GIS), and spatially distributed hydrologic models are commonly used to simulate hydrologic events for water resource management. In a DEM based hydrologic model, each cell represents a numerical element for model calculation. The average values of geometry and physical properties are expressed as characteristics of each cell, such as elevation, soil type, surface roughness, land cover, rainfall intensity, etc. According to existing distributed hydrology models, the assumptions of turbulent flow and representative flow velocity or discharge using a constant friction roughness are used for soil erosion calculations of every cell within the DEM. Many of the soil transport equations applied to a particular flow type may not be suitable for DEM based spatially distributed hydrologic models. A physically based regression method may be more appropriate to represent the soil erosion mechanics.

2.6.2 Model calibration

Using a distributed hydrology model, model parameters represent the physical or hydrologic characteristic of a watershed (Singh, 1995). These parameters such as flow resistance coefficients and soil infiltration rate need to be calibrated for the model application of a specific site. Split-sample and proxy-catchment methods are generally used for parameters calibration of hydrological models (Klemes, 1986; Chavoshian et al., 2006). In the split-sample method, calibration of model's parameter set is only possible if some observations (usually discharge data) are available to compare with predicted variables. The proxy-catchment method is to transfer parameters from a similar basin (proxy-catchment). It is usually used for a poor data basin and un-gauged watershed.

2.7 Digital Elevation Model (DEM) and Geologic Information System (GIS) Applications

Geologic Information System (GIS) can be used to provide a rapid assessment of the amount of erosion and its associated hazards. Many authors have demonstrated the potential for using digital elevation models in soil erosion assessment (Burrough, 1986; De Roo et al., 1989; Moore et al., 1992, 1993; Paringit and Kazuo, 2003; and Quinn et al., 1991). Existing studies suggest that using GIS, remote sensing and sediment transport models are effective methods to estimate and display the quantity and spatial distribution of sediment yield (Bartsch et al., 2002; Fernandez et al., 2003; Jain et al., 2001; and Bhuyan et al., 2002). GIS is a powerful tool to analyze spatial data. For example, Fernandez et al. (2003) estimated soil erosion and sediment yield using GIS, coupling with the Revised Universal Soil Loss Equation (RUSLE) and Sediment Delivery Distributed (SEDD) model. Bhuyan et al. (2002) assessed runoff and sediment yield using remote sensing, GIS, and the Agricultural Non-Point Source Pollution (AGNPS) model. Renschler (2003) developed a Graphic User Interface (GUI) built in ArcView named the GeoWEPP module (LESAM Lab. 2007). These studies have demonstrated the advantage of combining hydrologic models and GIS to determine erosion rate.

2.7.1 Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) is a basic element of spatially distributed models. Based on data from DEM, main watershed characteristics can be estimated and delineated to sub-basins or be modeled for each grid cell. Molnar and Julien (1998) and Kalin(2002) mentioned that a correction factor is needed for a raster size greater than 100m because different cell resolution causes different results for simulating hydrologic events. In this study, U.S. Geological Survey (USGS) raster DEM will be used in the distributed hydrologic model. The resolutions are 30m and 10m. Using different algorithm for calculating slope and flow direction can have different simulation results in DEM. Wolock and McCabe (1995), Tarboton (1997), and Holmgren (1994) discussed the effects of using different algorithms for a single flow direction and multiple flow directions. Their results indicate that the multiple flow directions algorithm is applicable for simulating saturated area in watersheds. Because soil particles are only carried by surface flow, the flow direction and its erosion capacity should be sensitive to overland soil yield rate and overland morphology. The two dimensional hydrology model, CASC2D (Julien et al., 1995), considers an algorithm for multiple flow directions and will be modified and improved for hydrograph and sediment graph simulations in this study

2.7.2 Hydrology/hydraulic engineering using Geographic Information System (GIS)

A geographic information system (GIS) is a computer-based system designed to store, process and analyze geo-referenced spatial data and their attribution (Jain and Goel, 2002). Using GIS, topographic and morphometric analysis may be carried out efficiently and different layers of information can be integrated. Jain and Kothyari (2000) stated that Geographic Information Systems (using traditional and remote sensing data) have been proven to play a very important role in analyzing soil erosion and sediment yield.

For example, a spatially distributed hydrology model has been incorporated in GRASS GIS by Stuebe and Johnston (1990). Vieux and Gauer (1994) developed a finite element model for simulating overland flow using a triangular irregular network (TIN) generated by ARC/INFO GIS. Maidment et al. (1996) provided a GIS-based methodology for generating unit hydrographs. Julien et al. (1995) developed CASC2D that utilizes a two-dimensional Saint Venant equation of mass and momentum conservation to represent the physics of overland flow incorporated in GRASS GIS. It can be said that no distributed hydrologic model is complete without some form of GIS platforms.

Tarboton's (2002) TauDEM, GeoWepp, Hec-GeoHMS, Hec-GeoRAS and Hydro Tools (Environmental Systems Research Institute, Inc., (ESRI), 2003) all have developed and coupled with ESRI's GIS desktops like ArcView 3.X (ESRI 2002), ArcMap 9.X and ARC/INFO. Those GIS platforms all were built with programming language for application. The AVENUE is built with ArcView 3.X, and VBA is built with ArcMap 9.X. Any one of the spatially distributed models can be coupled with a GIS platform using built programming language.

2.8 GIS Based Surface Soil Erosion Models

GIS is used for spatially distributed models and lump models for watershed sediment yield study. Based on the time scale, existing watershed sediment erosion models can be classified into long term predictors and event storm predictors. Usually, annual soil yield determination is seen as a long term predictor. For instance, the Universal Soil Loss Equation (USLE) and Revised Universal Soil-Loss Equation (RUSLE) are well-known models of long term soil yield prediction models. Both models were first developed for irrigation purposes and only applied in the United States. Garde et al. (1983) develop an annual sediment yield equation in India. These long term models are only applicable to certain locations and need to be revised before they can be applied to other locations.

For event based storm prediction, some of the existing models are MUSLE (Modified Universal Soil-Loss Equation), CASC2D-SED (CASCade 2 Dimensional SEDiment), WEPP (Water Erosion Prediction Project), ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation), CREAMS (Chemicals Runoff and Erosion from Agriculture Management System), LISEM (The Limgurg Soil Erosion Model), EPIC (Erosion Productivity Impact Calculator), EUROSEM (European Soil Erosion Model), and AGNPS (Agricultural Nonpoint Source) (Young, 1989). However, there is no generally accepted or "universal" model for erosion at the watershed scale (Kalin et al., 2003).

2.8.1 Annual soil erosion models

a. USLE-based models

The Universal Soil Loss Equation (USLE) (Wischmeier and Simith, 1978) and Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991) are the USLE-based models. They combine the soil erosion from different processes in the catchments into one equation. Empirical coefficients are used to present the rainfall characteristics, soil properties, ground surface conditions, etc (Kothyari et al., 2002). In GIS based USLE models, the USLE is adopted for the estimation of gross erosion rate in different overland cells or lump within a catchment. The soil erosion within a cell or lump is estimated using USLE, which is expressed as (Kothyari et al., 2002):

$$S_{E_i} = R \cdot K \cdot LS \cdot C \cdot P \tag{2.33}$$

where S_{E_i} = gross amount of soil erosion (t/ha); R = rainfall erosivity factor ($MJ \cdot mm/(ha \cdot h)$); K = soil erodibility factor ($t \cdot ha \cdot h/(ha \cdot MJ \cdot mm)$); LS = slope length and steepness factor; C = crop management factor; and P = land practice factor. The C factor is a weighted soil loss ratio based on the distribution of rainfall erosivity over the year (Pierce et al., 1986). It is complicated and highly empirical and is a function of land use, canopy cover, surface cover, surface roughness, soil moisture and treated as a resistance factor for long term soil erosion estimation. There are many methods available for the estimation of the LS factor (e.g. McCool et al., 1989; Moore & Wilson, 1992). Among these methods, the one that is best suited for integration with the GIS is the theoretical relationship proposed by Moore & Wilson (1992).

$$LS = \left[\frac{A_s}{22.13}\right]^n \cdot \left[\frac{\sin\theta}{0.0896}\right]^m \tag{2.34}$$

where A_s = unit contributing area (m^2/m), defined as the upslope contribution area for the overland grid per unit width normal to the flow direction; θ = slope gradient in degree; n = 0.4; and m = 1.3. The values for the factors K, C and P are computed for different grids on overland and channel regions according to Wischmeier & Simith (1978) using the classified satellite data for land cover and soil.

The USLE has not been developed for use at the catchment scale, since it does not simulate deposition. In GIS applications of USLE, a sediment delivery ratio (SDR) is suggested to define the ratio of sediment delivered at a location in the stream system to the gross erosion from the drainage area above that point. However, the existing SDR equations vary a lot by location. In addition, the USLE cannot be applied to extreme rainfall events.

b. Garde's 1983 Model

Sekhar and Rao (2002) identified soil erosion zones and suggested that appropriate measures for controlling soil erosion should use remote sensing, GIS and conventional techniques in the Phulang Vagu watershed in India. In their study, satellite images were interpreted to prepare land use and land cover maps by using the ERDAS images processing system. Next, their study used Garde et al.'s 1983 equations to determine the quantity of soil erosion. Finally, GIS was used to show and describe the quantity and spatial distribution of annual erosion.

The equation of Garde et al. (1983) is dependent on catchment area and annual runoff, as well as on other parameters such as slope, drainage density, annual rainfall and vegetative cover factor. The equation of Garde et al. (1983) is

$$V_{SAB} = 1.182 \times 10^{-6} \times A_w^{1.03} \times P_a^{1.129} \times R_m^{0.29} \times S^{0.08} \times D_d^{0.40} \times F_c^{2.52} \qquad (2.35)$$

where V_{SAB} = sediment yield in mm^{3}year^{-1}; A_w = watershed area in km^2; R_m = annual runoff in mm^2; S = average watershed slope; D_d = drainage desity in km^{-1}; F_c = vegetative cover factor; and P_a = annual precipitation in cm.

The area and distribution of land cover can be obtained satellite image processes. Vegetative cover factor F_c is calculated from the formula:

$$F_c = \frac{0.2F_1 + 0.2F_2 + 0.6F_3 + 0.8F_4 + F_5}{F_1 + F_2 + F_3 + F_4 + F_5} \qquad (2.36)$$

where F_1 = area under reserved and protected forest in km^2; F_2 = unclassified forest area in km^2; F_3 = cultivated area in km^2; F_4 = grass and pasture land in km^2; and F_5 = waste land in km^2.

2.8.2 Storm event soil erosion models

a. Modified Universal Soil-Loss Equation (MUSLE)

MUSLE (Williams, 1975) was developed to predicted sediment yields for individual storm events. It is expressed as

$$S_Y = 95(Q_v \cdot Q_p)^{0.56} K \cdot LS \cdot C \cdot P \qquad (2.37)$$

where S_Y= event sediment yield; Q_v = storm runoff volume in acre-ft; and Q_p = peak discharge in cfs. Eq. (2.36) should be used with caution because it was empirically developed based on limited data from Texas and the southwestern United States. The procedure should only be used on small watersheds (Ward and Trimble, 2004).

b. The Geo-spatial interface for the Water Erosion Prediction Project (GeoWEPP) Model

The WEPP model is a popular and comprehensive model and uses many techniques from other models such as CREAMS, EPIC, etc. Renschler (2001) developed the

Geo-spatial interface for WEPP based on GIS ArcView 3.2. The GeoWEPP is compatible with ArcView 3.X and ArcGIS 9.X (ESRI, 2007). There are four essential steps to derive topographical input parameters for WEPP watershed simulation, which is based on DEMs (Renschler, 2003):

1. Import of DEMs (public-domain software)
2. Channel and watershed delineation (TOPAZ; Garbrecht and Martz, 2000)
3. Model input parameters and model run (Avenue, C++ and FORTRAN)
4. Mapping model results (Avenue scripts)

In addition, GeoWEPP also provides tools that allow users to import or change soil and land use characteristics in the map view. After a project executes in GeoWEPP, it will create numerous outputs, including climate simulation, surface and subsurface hydrology, water balance, plant growth, residue decomposition and management, overland flow hydraulics, a hillslope erosion component, channel flow hydraulics, and channel erosion. Those results can all be displayed as text files and visualized as a map in ArcView.

c. CASC2D-SED model

Julien et al. (1995) develop CASC2D, which utilizes a two-dimensional Sain Venant equation of mass and momentum conservation to represent the physics of overland flow incorporated in GRASS GIS. The input data of CASC2D in GIS are DEM, soil property, land use, etc. The CASC2D-SED model includes hydrology and sediment yield models (Julien and Rojas. 2002). In CASC2D-SED, the overland erosion model uses modifications to the semi-empirical Kilinc and Richardson (1973) equation to estimate sediment yield as a function of unit discharge and land surface slope. This function is further modified by three of the six parameters from USLE. The relation is given by the following equation (Rojas, 2002):

$$q_s = 23210 \cdot q^{2.035} S_f^{1.664} \frac{KCP}{0.15} \quad (2.38)$$

where q_s = sediment unit discharge (ton/m/s); q = unit discharge of overland flow (m^2/s) (calculated within the overland flow component of CASC2D); S_f = friction slope; and K, C, and P = USLE parameters. Kilinc and Richardson (1973) equation, Eq. 2.21, was developed from simulated rainfall events. It might over-estimate soil erosion rate when there is only surface flow and no rainfall impacts.

According to Aksoy and Kavvas (2005), although runoff hydrographs were computed reasonably well using CASC2D, sediment graphs could not be simulated adequately. In this study, CASC2D will be used to simulate the runoff hydrograph. A new physically based overland flow erosion model will be developed to revise the overland erosion routing in Rojas's (2002) CASC2D-SED model.

2.8.3 Applications and limitations of erosion models

Because surface erosion is a complex process and there are a lot of factors involved in erosion mechanisms, there is no generally accepted or "universal" model for erosion at the watershed scale (Kalin et al., 2003). For existing watershed sediment yield models, Govers (1985), Kalin et al.(2003) and Ferro (1998) made the following observations:

1. Erosion models based on steady state assumptions cannot satisfy field conditions.

2. Models have limited range of application for particle size, watershed area, storm event, etc.

3. Erosion models cannot reflect extreme events such as extremal rainfall, hydraulic jump, and water fall.

4. Vegetation stems and boulders can cause more armoring effect.

5. Models aren't strong enough to predict the quantity of sediment supply.

6. There is a lack of understanding of the mechanisms of sediment deposition.

7. Assumed hydrology, morphometic and scaling properties are rarely met in natural watersheds.

8. Specific measurements from the field are needed.

It is essential for us to understand overland flow characteristics. In order to provide an appropriate estimate for overland sediment transport capacity and reduce the applicable limitations of the study results, overland flow properties are described in chapter three.

CHAPTER III OVERLAND FLOW PROPERTIES

One important aspect of this study is to understand the hydrologic characteristics of overland flow, including hydraulics and sediment transport. The characteristics of overland and channel flow are different. Differences in flow behavior contribute to the morphological development of watersheds. While channel flow is bounded by river banks, overland flow is controlled by the size of the contributing saturated area (Beven and Kirkby, 1979). Generally speaking, channel networks collect all kinds of runoff that are generated within the watershed, including overland flow, ground water inputs, and direct rainfall to the channel. Because a significant portion of flow in the channel network originates from the delivery of overland flow from upland areas of the watershed, overland flow is closely related to channel flow. Overland flow is the primary agent of transporting soil particles within a watershed. Van der Tak and Bras (1990), Julien (1985), Govers and Rauws (1986), and Singh et al. (2003) have illustrated the characteristics of overland flow. Landforms can be classified as hillslopes, rills, gullies and channels (Leopold et al, 1986). Different landforms contribute to different states of runoff in a watershed. Previous chapters illustrate some overland flow characteristics and related studies. In this chapter, overland flow will be thoroughly explained in terms of its hydraulic and sediment transport characteristics.

3.1 Comparisons between Overland Flow and Channel Flow

Van der Tak and Bras (1990) showed that overland flow velocity is typically an order of magnitude less than channel flow velocity. This velocity difference is a significant factor in the use of different methods between overland and channel flows. Singh et al. (2003), Julien et al. (1985), Govers and Rauws (1986), Merten et al. (2001), Tayfur and Singh (2004), Beven and Kirkby (1979) ,Ferro (1998), and Hairsine and Rose (1992a, 1992b) have described the characteristics of overland flow and soil particle movement. Based on their studies, the main characteristics of overland flow compared to channel flow are given as follows:

a. Flow Conditions

1. A very thin film of water covers the soil surface and is referred to as laminar sheet flow.
2. In laminar flow, viscous forces exceed inertial forces.
3. Sheet flow velocity is typically ten times less than channel flow velocity due to high friction roughness.
4. Channel flow is bounded by river banks, while overland flow is controlled by the size of the contributing saturated area.
5. Overland flow is produced from excess rainfall. Channel flow is generated from overland flow, inter flow, and ground water.
6. Form roughness is often much greater than grain roughness for overland flow.
7. Higher resistance in overland flow is due to flow viscosity, land cover, rain drops and form roughness.

8. Overland slopes are generally steeper than those of the channel beds.
9. Shallow surface flows are influenced by the impact of rain drops, which disturb flow condition and increase flow roughness.

b. Sediment Transport Conditions

1. Surface soils are the primary erosive materials for overland flow. The sources of sediment materials transported by channel flow come from uphill erosion, bank scour, and bed material.
2. Surface soil is mainly composed of silt, sand, and clay.
3. Due to highly disturbed flow and thin flow depth, the mixing length of sediment concentration is short. Overland flow sediment concentration immediately reaches equilibrium as the flow condition changes.
4. Due to high viscous forces and thin flow depth, the sediment transport capacity of sheet flow almost equals the bed load capacity.
5. Rain drops detach soil particles and decrease the critical condition of sediment incipient motion in which flow depth is thin.
6. Sediment on the land surface is generally cohesive.
7. Shield and armoring effects of land cover are easily observed.
8. As overland flow happens, most of the soil particles are transported as bed load by rolling, jumping or sliding on the ground.

Most existing research divides surface runoff into thread flow, sheet flow, inter-rill flow, rill flow, and gully flow based on morphologic characteristics (Moore and Burch, 1986; Guy et al., 1990; Hairsine and Rose, 1992a, 1992b). Because gullies grow by headward erosion or sapping, gully flow will be treated as channel flow in this study. Other flow stages will be described in section 3.3.

3.2 Saturated Contribution Area and Equilibrium Length

Although raindrops can detach soil particles from the ground surface, they still cannot convey soil particles downstream without overland flow transportation. Only the saturated area of a watershed can contribute runoff to the channel network (Beven and Kirkby, 1979). This is contributed from excess rainfall or saturated surface soil and runoff such as interflow. Fig. 3.1 illustrates the basic concept of saturated contribution area. Hall and Cratchley (2006) show an overland flow picture (Fig. 3.2) caused by excess rainfall on the River Mawddach Basin, North Wales, on the 3rd of July 2001. Within the saturated contribution area, overland flow can carry soil particles downstream to contribute sediment to channels and cause basin morphologic impacts on uphill erosion. Generally speaking, saturated contribution area is dominated by soil moisture, soil infiltration capacity, and rainfall intensity. Hence, a spatially distributed model should present the variation of saturated contribution area over time and also express the potential of surface erosion caused by overland flow.

Usually, overland flow is shallow and highly turbulent due to surface conditions. As sediment transport capacity is changed, the mixing length to achieve an equilibrium sediment concentration is very short. The study of Merten et al. (2001) shows that the equilibrium length is less than two meters. Tayfur and Singh (2004) mentioned that the sediment graph of overland flow reaches equilibrium very fast once the hydrograph reaches equilibrium. Therefore, an assumption of equilibrium state is acceptable for overland flow sediment calculation.

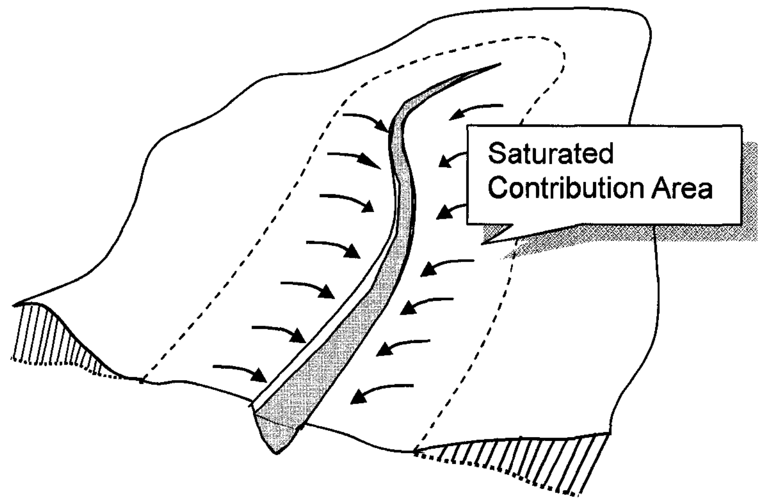


Figure 3.1. Saturated contribution area of watershed.

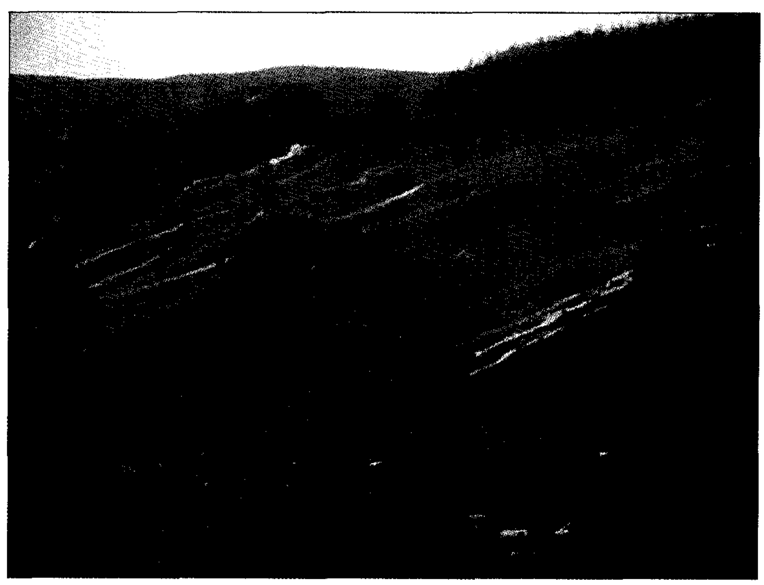


Figure 3.2. Overland flow caused by excess rainfall on the River Mawddach, North Wales, July 3, 2001 (Hall and Cratchley, 2006)

3.3 Overland Flow Stages and Important Physical Factors

According to previous studies, overland flow conditions and soil erosion rate vary with flow stages. In this study, relevant variables are grouped into rainfall impact, flow characteristics, and bed conditions. Fig. 3.3 illustrates overland flow conditions and surface soil erosion process on a plane and bare soil surface.

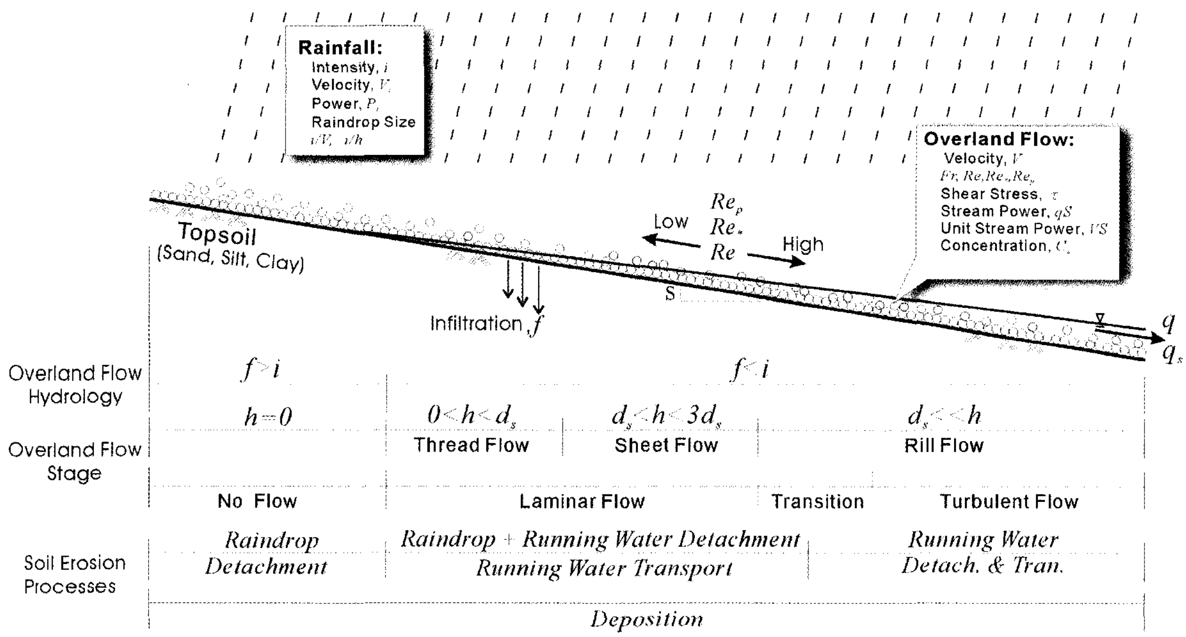


Figure 3.3. Particle detachment, transport, and deposition on bare soil surface

The physical parameters which can impact overland flow are described herein.

1. Rainfall Impact-

A review of previous studies has been described in Section 2.5. Raindrops hit the ground surface and detach surface particles from the soil mass. Soil particles may be deposited on the ground after detachment by raindrops if no excess surface runoff can transport those particles downstream. For shallow sheet flows, raindrops may disturb overland flow and reduce the critical condition of particle entrainment. Once particles are detached from ground surface, surface flow may carry particles downstream. In this case, flow and raindrops are dominant. As flow depth increases in the downstream direction, raindrop impact decreases, and surface flow dominates particle detachment and transport.

For overland flow and sediment transport, raindrops could disturb flow and increase hydraulic roughness. This may reduce flow velocity and increase sediment concentration. Therefore, rainfall intensity and spatial distribution are important factors in hydrologic studies. A physically based sediment transport capacity model should consider the effect of raindrops.

Once rainfall intensity i is greater than soil infiltration rate f_i, excess rainfall will become overland flow. In this study, rainfall influences are represented using rainfall intensity i, ratio of rainfall intensity to flow depth i/h (Ferro, 1998), rainfall velocity V_i, rainfall power P_i, and ratio of rainfall intensity to flow velocity i/V. The ratio of rainfall intensity to average flow velocity, i/V, can be seen as a dimensionless ratio between input flow length and lateral input flow depth per second per unit flow area.

2. Flow characteristics -

Based on basic assumptions of most sediment transport equations (Graf, 1971; Yang, 1972, 1973; Foster and Meyer, 1972, 1975), flow velocity V, stream power per unit width qS, unit stream power VS, or shear stress τ are considered as dominant variables. In addition to the above variables, energy slope S_f, unit discharge q, flow depth, Reynolds numbers (see Eqs. (3.2), (3.3) and (3.5)) and Froude number Fr are some of the physical parameters used by many investigators for the estimation of erosion and sediment transport rate. For overland flow, it is acceptable to assume that flow energy slope S_f is equal to bed slope S. Reynolds number is the ratio of inertial force to viscous force. Froude number is the ratio of inertial force to gravity force. These parameters are defined as follows.

Froude number:

$$Fr = \frac{V}{\sqrt{gh}} \tag{3.1}$$

where ν = kinematic viscosity of water; and g = gravitational acceleration.
Flow water Reynolds number:

$$Re = \frac{Vh}{\nu} \tag{3.2}$$

Grain shear Reynolds number

$$Re_* = \frac{u_* d_s}{\nu} \tag{3.3}$$

where shear stress velocity u_* is defined as

$$u_* = \sqrt{ghS} \tag{3.4}$$

Particle Reynolds Number:

$$Re_p = \frac{\omega \cdot d_s}{\nu} \tag{3.5}$$

The fall velocity ω of sand particles can be calculated by (Julien 1994)

$$\omega = \frac{8\nu}{d_s}\left[\left(1 + 0.0139 d_*^3\right)^{0.5} - 1\right] \tag{3.6}$$

where the dimensionless particle diameter d_* is defined as

$$d_* = d_s \left[\frac{(G-1)g}{\nu^2} \right]^{1/3} \tag{3.7}$$

where G = specific gravity of sediment particles. Usually, turbulent flow is defined as $Re > 2000$, $Re_* > 70$ or $Re_p > 1$.

3. Bed condition -

Bed roughness and particle entrainment can dissipate flow energy and decrease sediment transport capacity. On a plane surface, micro-topography has a significant effect on flow and flow erosivity. Bed particle size d_s can reflect grain roughness height. Bed particle size and relative submergence h/d_s or relative roughness d_s/h are used to express the bed condition in this study. Relative submergence can be used to represent flow stages. The flow conditions from upstream to downstream are:

(1) Thread flow, which integrates excess rainfall and runs around surface grains ($h/d_s \le 1$),

(2) Sheet flow, which is the integration of thread flow, and in which water level rises above roughness elements ($1 < h/d_s \le 3$), and

(3) Rill flow, which is small and parallel streamlets of water where sheet flow concentrates ($3 < h/d_s$).

For thread flow and sheet flow, surface flow is laminar and its boundary condition is hydraulically rough. Flow viscous force influence is significant. Once overland flow changes into rill stage, flow becomes turbulent, and the boundary is hydraulically smooth. Generally speaking, topsoil is the main material eroded by overland flow. For a very coarse sand plane ($d_s < 2mm$), overland flow is turbulent if the flow depth is deeper than 6*mm*. Flow is turbulent when particle size is finer than medium sand ($d_s < 0.25mm$) (Julien 1994). Considering bed form variation, raindrop disturbance, different land uses, and land cover impacts, overland flow within a watershed is mostly turbulent flow. A turbulent flow resistance equation can be used in the studies of overland flow erosion.

Flow energy can be dissipated by bed roughness, turbulent roughness, and sediment transport. According to Pearce (1976), most flow energy is dissipated by surface friction and only 3~4% of running water energy is expended in erosion. Yang (1979) suggested that incipient motion criteria can be disregarded when sediment concentration is greater than 100 *ppm* by weight, which is much less than that of overland flow. Therefore, the critical condition for particle entrainment in overland flow can be ignored.

To determine the significance of dominant factors and other important physical factors, correlation analyses of laboratory data are applied in Chapter Four.

3.4 Overland Flow Governing Equations

Flow resistance, momentum and continuity are the governing equations for overland flow hydraulic calculation. The continuity and sediment transport equations are the governing equations of sediment transport. Based on different flow conditions, governing equations are given in the following sections.

3.4.1 Flow resistance equations

In general, resistance to overland flow can be written as a stage-discharge relationship (Julien, 2002),

$$q = \alpha h^{\beta} \tag{3.8}$$

or as a stage-velocity relationship,

$$V = \alpha h^{\beta-1} \tag{3.9}$$

where q = unit discharge; h = flow depth, V = depth-averaged flow-velocity, and α and β = resistance coefficient.

There are two primary types of overland flow, laminar flow and turbulent flow. Shen and Li (1973) indicated that for a bare smooth surface, the flow is laminar when $Re <$ 900. The Blasius law is valid for turbulent flow when $Re > 2000$. Considering surface soil particles, on a bare soil surface, there are four principal types of flow investigated by Julien and Simons (1985) in soil erosion due to overland flow. They are (a) laminar sheet flow; (b) turbulent smooth flow governed by the Blasius equation; (c) turbulent rough flow (Manning equation); and (d) turbulent rough flow with very small relative roughness (Chezy equation). The last flow type is not very likely to occur in overland flow. In Julien and Simons's (1985) study, the Darcy-Weisbach friction factor f_d, as shown in Eq. (2.29), is used to represent the flow resistance of laminar flow based on surface conditions. For turbulent flows, the Manning equation is frequently used by engineers. For a bare soil surface, the Manning roughness coefficient, n_o, is usually considered as a function of relative roughness h/d_s.

Most existing distributed hydrology model treat the overland flow as turbulent flow. Based on the form of Eq. 3.9, resistance to overland flow can be written in terms of Darcy-Weisbach friction factor *f*, and Manning coefficient n_o. Their definitions are

$$V = \left(\frac{1}{n_o} S^{1/2} \right) h^{2/3} \quad \text{(Manning Equation in S.I. units)} \qquad (3.10)$$

$$V = \left(\sqrt{\frac{8g}{f}} S^{1/2} \right) h^{1/2} \quad \text{(Darcy-Weisbach Equation)} \qquad (3.11)$$

where *f* and n_o = resistance coefficients, which are constants and vary with land use, bed form, etc. For turbulent flow, $n_o = \sqrt{\frac{h^{1/3} f}{8g}}$ in S.I. units. Moore and Burch (1986) used Manning equation to build the relationship between runoff discharge and velocity:

Steady, Uniform Turbulent Kinematic Velocity:

$$q = Vh = \frac{1}{n_o} h^{5/3} S^{1/2} \qquad (3.12)$$

$$V = q^{0.4} \frac{S^{0.3}}{n_o^{0.6}} \qquad (3.13)$$

where V = velocity; n_o = Manning roughness coefficient of overland flow; h = overland flow depth; S = ground slope; and q = unit discharge per width. On the other hand, for laminar flow, velocity is more strongly affected by fluid properties (viscosity). Using the flow resistance equation developed by Potter et al. (1991), the relationship between discharge and velocity is described as follows:

Steady, Uniform laminar velocity:

$$V = \frac{\gamma_w}{3\mu} h^2 \sin\theta \cong \frac{\gamma_w}{3\mu} h^2 S \quad \text{(Potter et al., 1991)} \tag{3.14}$$

for $\theta < 5°$ or $S < 0.0875$

$$q = Vh = \frac{\gamma_w}{3\mu} h^3 S \tag{3.15}$$

$$h = \left(\frac{3\mu q}{\gamma_w S}\right)^{1/3} \Rightarrow V = \left(\frac{q^2 S \gamma_w}{3\mu}\right)^{1/3} \tag{3.16}$$

where γ_w = specific weight; and μ = dynamic viscosity.

Because of rainfall impact, bed form, and land cover, overland flow is turbulent in the field, and the Manning equation and a constant Manning roughness coefficient are used in most existing overland flow calculations. Table 3.1 lists the recommended Manning roughness values of different land covers provided by USACE (1998). The Manning roughness values of open channel flow shown in Table 3.2 suggest that the roughness values of bare soil surface and channel flow are similar. However, when the impacts of land covers such as vegetation, crops, etc are considered, the Manning roughness coefficients can increase ten times and cause a reduction in flow velocity. Consequently, land cover and land use are dominant factors of flow resistance for overland flow.

Table 3.1. Overland-flow coefficients for sheet-flow model (USACE, 1998)

Surface Description	n_o
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤ 20%	0.06
Residue cover > 20%	0.17
Grass:	
Short grass prairie	0.15
Dense grasses, including species such as weeping love grass, bluegrass, buffalo grass, blue grass, and native grass mixtures	0.24
Bermuda grass	0.41
Range	0.13
Woods [1]	
Light underbrush	0.4
Dense underbrush	0.8

Notes:

1 When selecting *n*, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

Table 3.2. Channel-flow coefficients for channel-flow modeling

Main Channel Description	n_c
Sand bed[2]	0.012~0.026
Concrete bed[2]	0.012~0.018
Gravel bed[2]	0.028~0.035
Natural Streams[1]	0.025~0.150
Mountain Streams[1]	0.030~0.070

Notes:

1 Chow (1964)

2 Aldridge and Garret (1973)

In hydrology models, concentration time t_{ci} of surface runoff is lagged using a roughness coefficient which is used to reflect all resistance factors. Fig. 3.4 explains that the concentration time and instantaneous discharges are controlled by roughness factors before discharge reaches equilibrium when rainfall intensity is constant.

Considering all the effective factors of overland flow resistance, the Manning's roughness coefficient, n_o, is a function of many factors:

$$n_o = f(n_d, n_f, n_L, n_i, n_s, n_m) \quad (3.17)$$

where n_d = relative roughness as a function of flow depth and particle size; n_f = bed form roughness as a function of bed topography; n_L = land cover roughness due to different land covers and land uses; n_i = rain drop disturbance roughness; n_s = flow lag roughness due to land cover interception; and n_m = flow resistance from soil infiltration impact. In practice, because rainfall intensity, infiltration, saturated area, and interception all vary by time and locations, runoff from a catchment cannot reach equilibrium.

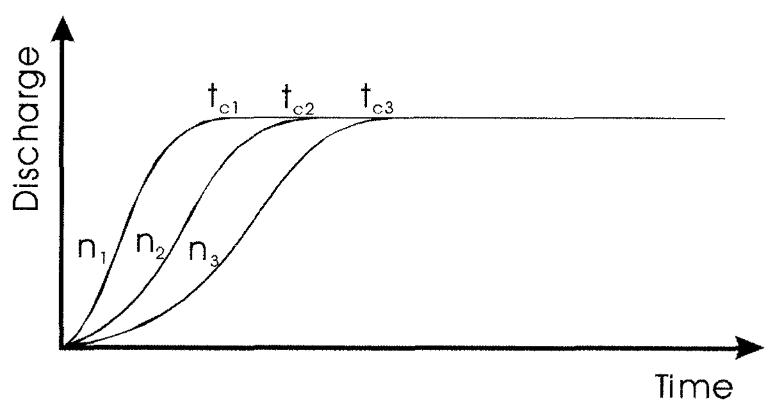


Figure 3.4. Overland roughness impacts for hydrographs.

In existing distributed hydrology models, the available cell size ranges from 10 square meters to several acres. It is a general practice to use the Manning equation for each calculation cell. The use of a representative roughness coefficient is common to represent the average flow resistance of each cell. However, there are various field conditions involved in each calculating cell, and channel network density can be changed by different cell resolution. Therefore, values of resistance coefficients need to be calibrated using field information such as flow gauge data. In this study, overland flow is modeled as turbulent flow. The Manning equation and the Manning roughness coefficients are used to simulate overland flow conditions.

For fluvial flow and overland flow, sediment transport studies consider flow velocity, shear stress, stream power, or unit stream power to be a dominant factor for sediment transport capacity. A flow resistance equation is usually used to compute flow velocity or flow depth. The computed flow velocity and depth can be altered by changing the roughness coefficient value in a flow resistance equation. This explains why sediment transport capacity can vary with dominant factors although flow rate reaches equilibrium. For overland flow, the effects of land covers and land uses should also have noticeable impacts on surface soil erosion. In this study, flow resistance is represented by using a roughness coefficient. The sensitivity of using different roughness coefficients to estimate sediment transport capacity is discussed in Chapter Six.

3.4.2 Flow momentum equations

Daluz-Vieira (1983) stated that the propagation of shallow waves in open channel or overland flows can be described using the full Saint-Venant equations, which are based on the following assumptions:

a. One-dimensional flow

b. Gradually varied flow

c. The channel is approximately straight

d. Small river bed slope and fixed river bed

e. Manning's equation is applicable

f. Incompressible and constant density

As presented below, Eq. (3.18) is the Saint-Venant equation that neglects eddy losses, wind shear effects, and lateral inflow. It further assumes that the momentum coefficient (β) is unity. Other terms in the equation express the influence of friction, inertial, and gravity forces.

The total energy of a flow is readily expressed in units of length as the total head of water. In terms of head, the total energy is equal to the sum of the elevation above a reference datum, the pressure head, and velocity head as presented in Eq. (3.19), which is known as the Bernoulli equation for steady flow in an incompressible fluid.

Taking the bottom of a sheet flow as the x axis and differentiating Eq. (3.19) with respect to length x of the water surface profile yields Eq. (3.20). Rearranging Eq. (3.20) and expressing the spatial derivative terms (dH/dx) as slope yields Eq. (3.21). Except for the local acceleration term, Eq. (3.18) and Eq. (3.21) are similar in form. The only energy dissipation term in the Saint-Venant equation is the energy loss due to friction, which can be computed by using a flow resistance equation.

Saint-Venant Equation:

$$\frac{1}{h}\frac{\partial q}{\partial t} + \frac{1}{h}\frac{\partial (q^2/h)}{\partial x} + g\frac{\partial h}{\partial x} - g(S - S_f) = 0 \qquad (3.18)$$

Local acceleration term	Convective acceleration term	Pressure force term	Gravity force term	Friction force term

Steady, uniform flow: gravity and friction force terms

Steady, nonuniform flow: convective acceleration term through friction force term

Unsteady, nonuniform flow: local acceleration term through friction force term

Bernoulli's Equation:

$$\frac{V^2}{2g} + h + H_Z - H_T = 0 \qquad (3.19)$$

Velocity head	Pressure head	Elevation head	Total head

$$V\frac{dV}{dx} + g\frac{dh}{dx} + g\left(\frac{dH_z}{dx} - \frac{dH_T}{dx}\right) = 0 \qquad (3.20)$$

$$V\frac{dV}{dx} + gS_w - g(S - S_f) = 0 \qquad (3.21)$$

Kinematic Wave: gravity and friction terms

Diffusive Wave: pressure through friction terms

Quasi-steady Wave: convective acceleration through friction terms

Dynamic Wave: all terms

where q = unit discharge; h = flow depth; S_w = water surface slope; t = time; S = bottom slope; S_f = energy slope; H_z = elevation head; and H_T = total energy head.

The complete Saint-Venant equation consists of the kinematic wave, the diffusive wave, the quasi-steady wave, and the dynamic wave equations. Among these simplified formulas, kinematic wave routing governs flow when inertial and pressure forces are not important and the backwater effect from downstream can be neglected. Thus, for kinematic wave, the gravity and friction force must be balanced. This method has been shown to be a good approximation for most overland flows (Kibler and Woolhiser, 1970).

Regarding overland flow sediment transport, kinematic wave routing may cause an over estimation of deposition within given calculation cells with equal elevation such as lakes and flat plans because of the assumption that bed slope is equal to energy slope. Julien et al. (1995) developed a two-dimensional rainfall-runoff watershed model (CASC2D). That model has been tested and proven to be more accurate by using two-dimensional diffusive overland flow routing (Johnson et al., 2000). Therefore, diffusive wave routing is applied to simulate overland flow in this study.

3.4.3 Flow continuity equation

For a unit width, the continuity equation for overland flow is

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=i-f_i \tag{3.22}$$

where i = rainfall intensity; and f_i = soil infiltration rate on ground surface. The use of Horton's (1935) equation and Green and Ampt's (Green and Ampt, 1911; Mein and Larson, 1973; Rawls and Brakensiek, 1983) equation are the most common methods to estimate the infiltration rate in existing distributed hydrology models. In Rojas's (2002) CASC2D-SED model, the Green and Ampt equation was used to compute infiltration rates in a simulation event.

3.4.4 Analytic solution of overland flow hydrology

For fully turbulent flows, analytic solutions of overland flow hydraulics are explained in Appendix B. The analytic solution of kinematic wave routing is

$$\frac{\partial h}{\partial t}+c_k\frac{\partial h}{\partial x}=i-f_i \tag{3.23}$$

where c_k = wave celerity defined as $c = \beta V$. $V = \frac{1}{n_o} h^{2/3} \sqrt{S_f}$ and $\beta = \frac{5}{3}$ if Manning equation is used. Energy slope $S_f = S$ and n_o = Manning roughness coefficient.

The analytic solution of diffusive wave routing is

$$\frac{\partial h}{\partial t} + c_d \frac{\partial h}{\partial x} + D_d \frac{\partial^2 h}{\partial x^2} = (i - f_i) \tag{3.24}$$

where c_d = the diffusive wave celerity defined as $c_d = \frac{dq}{dh} = \beta V$; and D_d = the hydraulic diffusivity defined as $D_d = \frac{q}{2S_0}$. $V = \frac{1}{n_o} h^{2/3} \sqrt{S_f}$ and $\beta = \frac{5}{3}$ if Manning equation is used. Energy slope $S_f = S - \frac{\partial h}{\partial x}$ and n_o = Manning roughness coefficient.

The term of $D_d \frac{\partial^2 h}{\partial x^2}$ represents the diffusion of a flood wave as it travels on overland surface. It can be disregarded when the bed slope is steep, or flow depth is shallow. Then, remaining equation of Eq. (3.24) is expressed as

$$\frac{\partial h}{\partial t} + c_d \frac{\partial h}{\partial x} \cong (i - f_i) \tag{3.25}$$

This is the same as the equation for kinematic wave routing in Eq. (3.23)

3.4.5 Continuity equation and sediment transport equation

For overland flow, sediment transport rate is controlled by sediment supply from the ground surface and sediment transport capacity for running water. The continuity equation normally used in dynamic upland erosion models is

$$\frac{\partial q_s}{\partial x}+\frac{\partial (C_s h)}{\partial t}=E_e-D_s \quad (3.26)$$

where E_e = soil erosion rate by overland flow; and D_s = particle deposition rate. Referring to section 3.2, the equilibrium length of soil mixing is very short. That means the sediment supply and transport capacity can be treated as being in balance. Therefore, a quasi-steady sediment movement is a reasonable assumption. The simplified equation is

$$\frac{\partial q_s}{\partial x}=E_e-D_s \quad (3.27)$$

Sediment transport rate carried by overland flow can be expressed as

$$q_s=q\cdot C_s \quad (3.28)$$

where q = unit discharge of running water; and C_s = sediment concentration. Formulas of overland flow sediment transport were introduced in section 2.4. Usually, overland flow sediment transport capacity is expressed by a sediment transport rate, q_s, or by a sediment concentration, C_s. However, using a q_s equation cannot show the maximum sediment concentration limit. This study suggests using a C_s equation for overland flow sediment transport calculation.

CHAPTER IV ESTIMATE OVERLAND FLOW SEDIMENT TRANSPORT CAPACITY ON BARE SOIL SURFACE

Soil erosion is a two-phase process consisting of detachment and transport of individual soil particles from soil mass. Rain-splash and running water are two of the most important detaching agents to remove soil particles from the soil surface. Detached soil particles are transported by running water. When sufficient energy is no longer available to transport soil particles, a third phase, deposition, occurs.

Surface soil erosion is an integrated process of rainfall splash detachment, sheet flow erosion, inter-rill flow erosion, and rill flow erosion. Most erosive materials are topsoil which is mainly composed of sand, silt, and clay. Surface soil erosion is a complicated problem affected by micro-topography, land cover, surface material, flow characteristics, boundary conditions, etc. Numerical models are often used to predict surface soil erosion processes in a watershed. Each calculating element in a numerical model contains information on micro-topography, flow type, and flow characteristics. It is difficult to have an analytic solution to predict soil erosion processes. Therefore, regression approaches using physically based parameters should be used to estimate surface erosion rate.

4.1. Power Function Based Equations and Physically Dominant Variables

Due to the large number of variables involved in complicated hydrologic and hydraulic problems, the power function type of models are often used to obtain statistical solutions. The formulas are illustrated in section 2.4.2. In a laboratory, unit discharge and surface slope can be directly measured as significant dominant factors. The sediment concentration C_s of overland flow is treated as a function of unit discharge and bed slope.

$$C_s = \alpha \cdot q^{\varepsilon} S^{\beta} \qquad (4.1)$$

where ε, α and β = coefficients which should vary with flow and surface conditions. When ε and β are constant, Eq. (4.1) only shows a point in Fig. 2.5 and represents a special hydraulic condition. One of the main goals in this study is to develop a new overland flow soil transport equation which has a wider coverage in Fig. 2.5. So, the new equation can represent more hydraulic conditions than that using Eq. (4.1).

For alluvial beds, the sediment bed material load equations can be expressed by the following basic form (Graf, 1971; Yang, 1972; Foster and Meyer, 1975; Bagnold, 1956):

$$C_s = A \cdot \Omega_e^{\ B} \qquad (4.2)$$

where A and B = parameters related to flow and sediment conditions; and Ω_e = effective dominant variable. The mechanism of overland flow sediment transport can be treated as bed material load transport. Therefore, Eq. (4.2) can be used to estimate overland flow erosion capacity. Previous studies suggest that flow rate, flow velocity, shear stress, stream power, unit stream power, or dimensionless unit stream power may be a dominant factor for overland flow sediment transport. In this study, bed material load formula Eq. (4.2) with a dominant variable will be used to reflect the sediment transport capacity based on flow hydraulic conditions. By converting Eq. (4.2) to Eq. (4.1), the described area using Eq. (4.2) is shown as a line on Fig. 2.5.

The basic forms of overland flow erosion equation can be expressed as

Foster and Meyer (1972) and Gilley et al. (1985)-

$$q_s = A \cdot V^B \tag{4.3}$$

$$q_s = A \cdot q^B = A \cdot (V \cdot h)^B \tag{4.4}$$

$$q_s = A \cdot \tau^B = A \cdot (\gamma \cdot h \cdot S)^B \text{, or } q_s \propto A \cdot (h \cdot S)^B \tag{4.5}$$

Yang (1972)-

$$q_s = A \cdot (\gamma \cdot VS)^B \text{ , or } q_s \propto A \cdot (VS)^B \tag{4.6}$$

Bagnold (1966)-

$$q_s = A \cdot (\tau V)^B = A \cdot (\gamma \cdot h \cdot S \cdot V)^B \text{ , or } q_s \propto A \cdot (h \cdot S \cdot V)^B \tag{4.7}$$

Chang (1979)-

$$q_s = A \cdot (\gamma \cdot qS)^B = A \cdot (\gamma \cdot h \cdot S \cdot V)^B \text{ , or } q_s \propto A \cdot (h \cdot S \cdot V)^B \tag{4.8}$$

The following dimensionless forms of unit stream power have been used for sediment transport studies.

Yang (1973)-

$$q_s = A \cdot \left(\gamma \cdot \frac{VS}{\omega} \right)^B \text{ , or } q_s \propto A \cdot \left(\frac{VS}{\omega} \right)^B \tag{4.9}$$

Vanoni (1978)-

$$q_s = A \cdot \left(\gamma \cdot \frac{VS}{\sqrt{g \cdot d_s}} \right)^B \text{, or } q_s \propto A \cdot \left(\frac{VS}{\sqrt{g \cdot d_s}} \right)^B \tag{4.10}$$

This Study-

$$q_s = A \cdot \left(\gamma \cdot \frac{VS}{\sqrt{g \cdot h}} \right)^B \text{, or } q_s \propto A \cdot \left(\frac{VS}{\sqrt{g \cdot h}} \right)^B \tag{4.11}$$

where γ = specific weight of water, which is treated as a constant in this study; VS = unit stream power per unit weight of water; VS/ω, $VS/\sqrt{gd_s}$, and $VS/\sqrt{g \cdot h}$ = dimensionless unit stream power per unit weight of water; τV = stream power per unit bed area; and qS = stream power per unit width. Eqs. (4.7) and (4.8) show that τV and qS have the same dimension for overland flow.

4.1.1 Equation coverage using different suggested dominant factors

Flow velocity and depth can be expressed by q and S in a power function formula. For turbulent flow based on the Manning equation, the flow velocity and depth can be expressed as

$$V = \left(\frac{1}{n^{0.6}} \right) \cdot q^{0.4} S^{0.3} \tag{4.12}$$

$$h = n^{0.6} \cdot q^{0.6} S^{-0.3} \tag{4.13}$$

Then, shear stress τ, unit stream power VS, and stream power per unit width τV can be shown as

$$\tau = \gamma \cdot n^{0.6} \cdot q^{0.6} S^{0.7} \tag{4.14}$$

$$V \cdot S = \left(\frac{1}{n^{0.6}}\right) \cdot q^{0.4} S^{1.3} \tag{4.15}$$

$$\tau \cdot V = \gamma \cdot n^{0.6} \cdot q^{1} S^{1} \tag{4.16}$$

Then, Eq. 4.2 can be expressed by using different dominant factors and flow conditions. Those equations are shown in Table 4.1. In Table 4.1, the parameter A is a function of roughness friction and flow characteristic.

Table 4.1. Power functions based on using Eq. (4.2) with different dominant factors and flow conditions.

ID	Ω_e	Formula	Flow Condition	Note
1	V	$C_s = A \cdot \left(q^{0.4} S^{0.3}\right)^B$	Turbulent Flow	Sheet Flow
2	V	$C_s = A \cdot \left(q^{0.667} S^{0.333}\right)^B$	Laminar Flow	Sheet Flow
3	VS	$C_s = A \cdot \left(q^{0.667} S^{1.333}\right)^B$	Laminar Flow	Sheet Flow
4	VS	$C_s = A \cdot \left(q^{0.25} S^{1.375}\right)^B$	Turbulent Flow	Rill Flow (Moore & Burch, 1986)
5	VS	$C_s = A \cdot \left(q^{0.4} S^{1.3}\right)^B$	Turbulent Flow	Sheet Flow
6	VS	$C_s = A \cdot \left(q^{0.625} S^{1.25}\right)^B$	Laminar Flow	Irregular Bed (Govers & Rauws, 1986)
7	τ	$C_s = A \cdot \left(q^{0.6} S^{0.7}\right)^B$	Turbulent Flow	Sheet Flow
8	τ	$C_s = A \cdot \left(q^{0.333} S^{0.667}\right)^B$	Laminar Flow	Sheet Flow
9	qS and τV	$C_s = A \cdot \left(q^{1} S^{1}\right)^B$	Laminar & Turbulent Flow	Sheet Flow

When parameter B is varying with flow conditions, the exponent terms, which are $(\varepsilon \cdot B)$ of q and $(\beta \cdot B)$ of S, are drawn as lines in Fig. 4.1. Each relationship is expressed by a line with a slope $S_{\Omega} = \frac{\beta}{\varepsilon}$. In order to compare with empirical studies, the lines of ε versus β based on different flow types using different dominant factors are drawn on Fig. 4.1. The vertical line ($C_s \sim S^{\beta}$) shows that sediment concentration is dominated by slope. The horizontal line ($C_s \sim q^{\varepsilon}$) shows that sediment concentration is dominated by unit discharge. Based on the boundaries of these empirical studies, the sediment transport capacities are dominated by slope and flow velocity ($C_s \sim V^{B}$). The area within lines No. 3, No. 4, No. 5 and No. 6 are the majority and has coverage of 67% within these empirical studies. These lines are based on the unit stream power for different types of flow. The results show that the using the unit stream power produce a very good ability to estimate overland flow erosion capacity.

In order to increase the coverage beyond a point or a single line in Fig. 4.1, unit stream power could be the dominant variable in Eq. (4.2), and the parameters A and B of Eq. (4.2) should have an ability to consider the enhancements of slope and flow velocity, which vary with different flow conditions. This means that A and B should include important physical factors for overland flow sediment transport. The significance verification of unit stream power, slope, and flow velocity are described in sections 4.4 and 4.5 by published experimental data and correlation analyses.

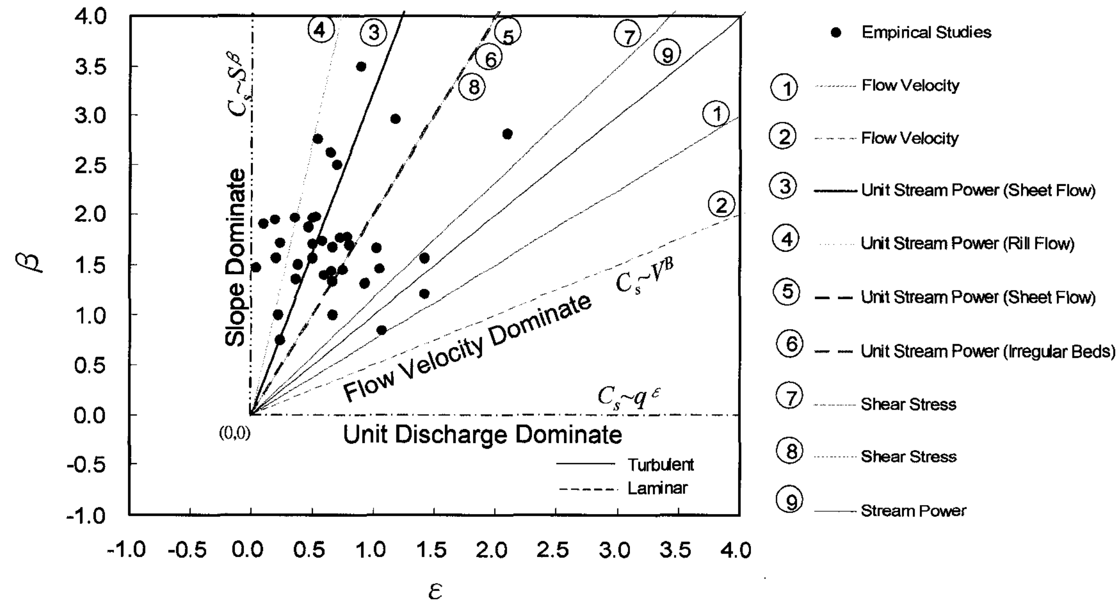


Figure 4.1. ε versus β plot of different flow types and dominant factors

According to Table 4.1, the suggested dominant factors of overland flow sediment transport can be transformed into a power function formula of q, S, with a roughness term. The roughness terms are different when using different dominant factors. For example, the roughness term of velocity is $1/n^{0.6}$ in Eq. (4.12), and the roughness term of shear stress is $n^{0.6}$ in Eq. (4.14). According to the physical meaning of each dominant factor, it tells us that the roughness term has been included in the dominant factor used when the power function form of q and S with physical factors is used to estimate erosion capacity. In other words, the dominant factors are used to estimate soil erosion, including the impacts of flow resistance. In this study, a dominant factor is used in the development of soil erosion model. The erosion model will be validated using a one-dimensional model and a revised CASC2D-SED model.

4.1.2 Soil erosion potential and resistance factors

For surface erosion, running water is the primary agent to transport soil particles. Overland flow is produced from excess precipitation. In empirical models, flow rate and potential energy are usually used to describe soil erosion potential. Table 4.2 shows the erosion potential term, and efficiency terms of USLE, MUSLE, and CASC2D-SED models. Because Kilinc's (1972) equation, Eq. 2.2, is an empirical equation, Julien (1995) added the *C* factor as a resistance term.

Table 4.2. Erosion potential and resistance factors.

Model	Erosion Potential Term (Erosivity)	Efficiency Term (Erodibility)		
		Resistance Factors	Soil Erodibility Factor	
USLE	$R \cdot LS$	$C \cdot P$	K	Long Term
MUSLE	$95(Q_v Q_p)^{0.56}$	$C \cdot P$	K	Storm Events Based
CASC2D-SED	$\frac{23210}{0.15} \cdot q^{2.035} S^{1.664}$	$C \cdot P$	K	Storm Events Based

Excluding any resistance and limitation, erosion potential terms present the maximum soil erosion capacity. Crop management factor *C*, erosion control practice factor *P*, and soil erodibility factor *K* are the controllable factors to reduce the soil loss to a predetermined value. Generally speaking, high resolution DEM data can describe the flow direction and bed slope due to macro-topographic changes such as terraced fields. With no erosion control practice, $P = 1.0$. *K* varies with different bed materials. *C* is the most computationally complicated of the USLE factors. It incorporates effects of tillage management (dates and types), crop, seasonal erosivity index (R) distribution, cropping history (rotation), and crop yield level (organic matter production potential)

(Line and Foster, 1996).This factor is the ratio of soil loss from land cropped under specified conditions to corresponding loss under tilled, continuous fallow conditions. For an event based simulation, these factors may not be all significantly effective to overland flow erosion. For an event based overland flow erosion model, flow resistance and soil erodibility may be the dominant factors for sediment yield to affect soil erosion capacity because overland flow is the primary agent. Overland flow characteristics can be significantly changed by different land covers. Fig. 4.2 shows that the flow depth and velocity vary with roughness at constant unit discharges. This indicates that a constant discharge can have various sediment transport capacities when flow resistance changes. In addition, the flow resistance can be considered in flow governing equations and directly express its impacts on physical factors such as flow velocity, depth, unit stream power, and shear stress. The crop management factor C is only an empirical coefficient, and does not have a strong relationship with empirical equations using q and S.

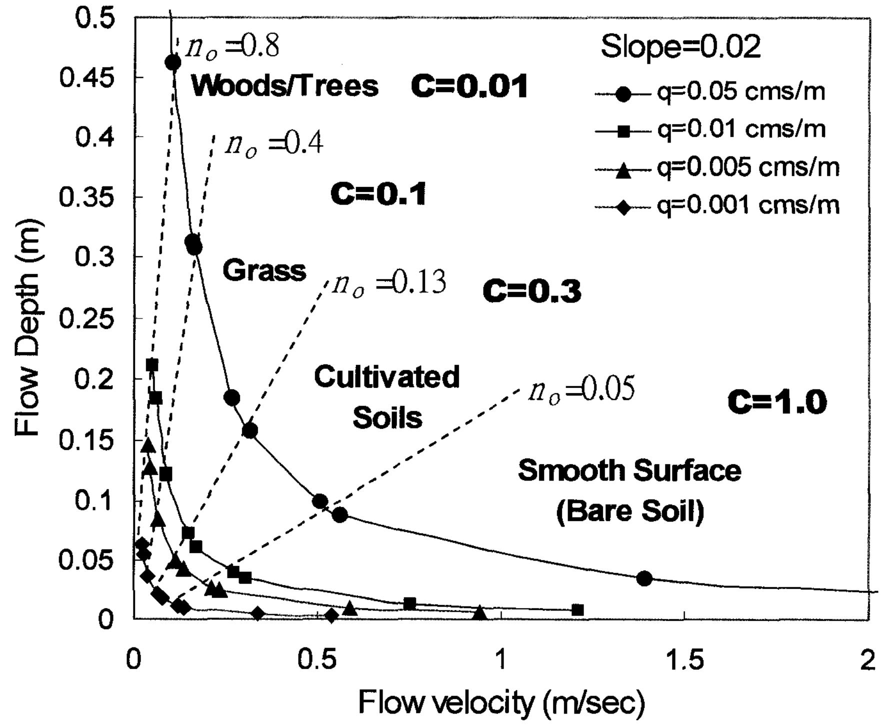


Figure 4.2. Flow characteristics affected by resistance factors, Manning roughness n_o and crop management factor *C* for different unit discharges.

4.1.3 Comparison of using USLE *C* factor and Manning n_o

According to the sections 3.4 and 4.1.2, the USLE *C* factor has been used to represent the resistance for flow and soil together. A Manning n_o has been integrated in hydraulic governing equations to physically express the resistance for flow. The sediment transport capacity is strongly relative to flow characteristics like velocity, slope, flow depth, shear stress, etc. A comparison of using USLE C factor and using Manning n_o to represent resistance in soil erosion models is shown in Table 4.3.

Table 4.3. Comparison of using USLE C factor and using Manning n_o.

Factor	C	n_o
Property	Empirical	Empirical
Estimation of flow sediment transport capacity	Empirical equation $\cdot C$	Integrated in the governing eqs: Continuity, momentum, flow resistance, and sediment transport.
Effects	To represent resistances directly to flow and soil together.	To represent flow resistances, and then, affects the sediment transport capacity by using governing eqs.
Relevance References	Most were done for agriculture uses.	A lot of studies were done for different land uses and land covers
Time scale	Annual (Long term)	Instant (Short term, event-based)
Note	Still need a flow roughness coefficient for discharge computation in a spatially distributed model.	Sediment transport equations should include hydraulic parameters. A no can be used for hydraulic parameter computation.

4.2 Experimental Data of Overland Flow Sediment Transportation

4.2.1 Published experimental data

In this study, laboratory data are used for regression analysis, and experimental field data are used for model validation. The data sources, scale, material and other information are given in Appendix C.

In order to increase the statistical significance of regression analysis, a large number of samples are needed. Laboratory data by Kilinc (1972), Aziz and Scott (1989), and Guy and Dickinson (1990) are used to determine the significance of physical parameters for the development of regression equations to estimate surface soil erosion rate. A total of

158 sets of data, including 42 sets of data taken from simulated rainfalls, are used in this study (Table 4.4). On the bare soil surface, the relative factors for overland flow erosion are described in section 3.3. They are used in the regression analysis. The ranges of each parameter are presented in Table 4.5. Mean particle size (d_{50}) is used to represent the particle size (d_s), and flume slope or soil surface slope (S) is assumed to equal the energy slope for overland flow.

Table 4.4. Sources of published experimental data for overland flow sediment transport.

Sources	Flow	Rainfall Events	Sub Total
Kilinc (1972)		24	24
Aziz & Scott (1989)	96		96
Guy and Dickinson (1990)	20	18	38
Total	116	42	158

Table 4.5. Summary of published experimental data for overland flow sediment transport.

Parameter	Concentration C_{mgl}	d_{50} (mm)	Slope (m/m)	Rainfall intensity (mm/hr)	Unit flow discharge (m^2/s/m)	Flow Depth h (mm)
Max	612504	1.0	0.4	223	0.004732	11.6
Min	959	0.2	0.02	32	9.07E-06	0.2
Parameter	Flow Velocity V (m/s)	VS (m/s)	qS (cms/m)	τ (N/m^2)	Re	Re_*
Max	0.706	125.73	0.4637	0.866	54.806	94.5
Min	0.019	0.38	0.0002	0.007	0.002	1.9
Parameter	Fr	h/d_s Relative Submergence	Rain fall velocity V_i (m/s)	Rainfall Power P_i (kg/sec)	i/V	i/h (1/sec)
Max	4.61	29.95	3.35	0.35	0.0013	0.151
Min	0.27	0.99	2.92	0.035	7.16E-05	0.018

According to the range of Reynolds number, *Re*, for rigid boundary, all flows in Table 4.3 are laminar. From the range of grain shear Reynolds number, Re_*, the data include laminar and turbulent flow conditions. Hydraulically smooth and hydraulically rough conditions can be represented by the relative submergence, h/d_s. When the relative submergence increases, the flow condition tends to be hydraulically smooth. Conditions of sub-critical flow and super-critical flow are determined by Froude number.

4.2.2 Relationships between flow resistance and hydraulic parameters

In general, flow resistance can be expressed as a function of hydraulic parameters such as flow depth, unit discharge, Reynolds number, and Froude number. Based on the measured mean values of flow velocity, flow depth, and unit discharge, the values of Reynolds number and Froude number can be computed. The Manning equation (Eq. 3.10) and Darcy Weisbach equation (Eq. 3.11) are commonly used to compute flow velocity and discharge for overland flow. The coefficients, which are f and n_o, express flow resistance. Based on the published experimental data used in this study, the relationship between hydraulic parameters, which are flow depth, flow velocity, *Fr*, and *Re*, and flow resistance coefficients are shown in Figs. 4.3 and 4.4. Because of lack of temperature information, a constant water kinematic viscosity of $1.0 \cdot 10^{-6}$ is used to compute flow Reynolds numbers.

In Fig. 4.3, all of relationships between coefficient f and hydraulic parameters are not strong. According to previous studies, Eq. 2.30 is usually used to describe the flow resistance of sheet flow. A $K_t = 24$ is representative of a smooth surface (Li and Shen, 1973). The value of K_t increases when flow resistance increases due to surface roughness and rainfall intensity. Because of raindrop detachment, surface flow erosion, and irregular soil surface, concentrated flows such as thread flow and rill flow occur on the experimental flumes and plots. The concentrated flow may have higher velocity than the thin sheet flow and reduces the travel time on the soil surface. This condition results that the measured average flow velocity increases, and the representative values of flow coefficient f and Reynolds number reduce. Fig. 4.3.d shows that the value of coefficient f decreases due to the concentrated flows occurring. In this case, although the mean Reynolds number indicate the flow is laminar, the hydraulic characteristics of the concentrated flow may be turbulent.

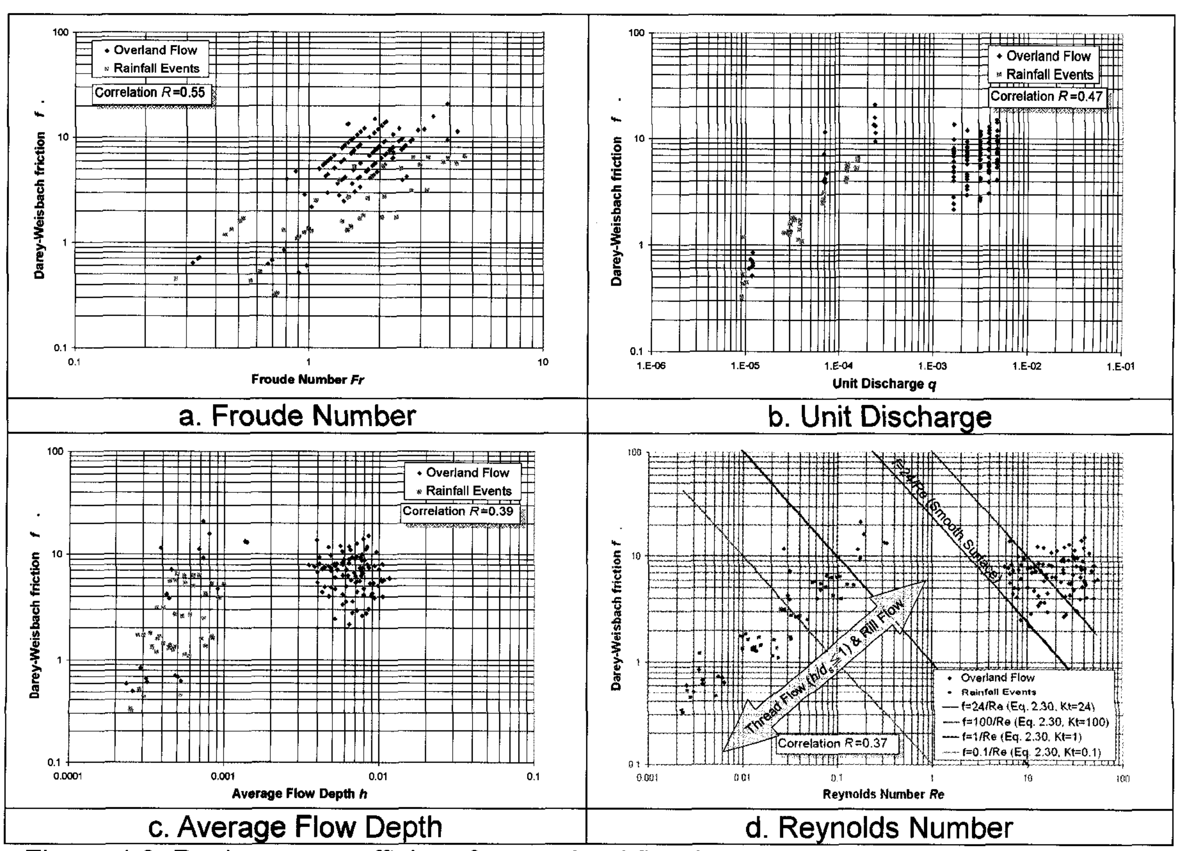
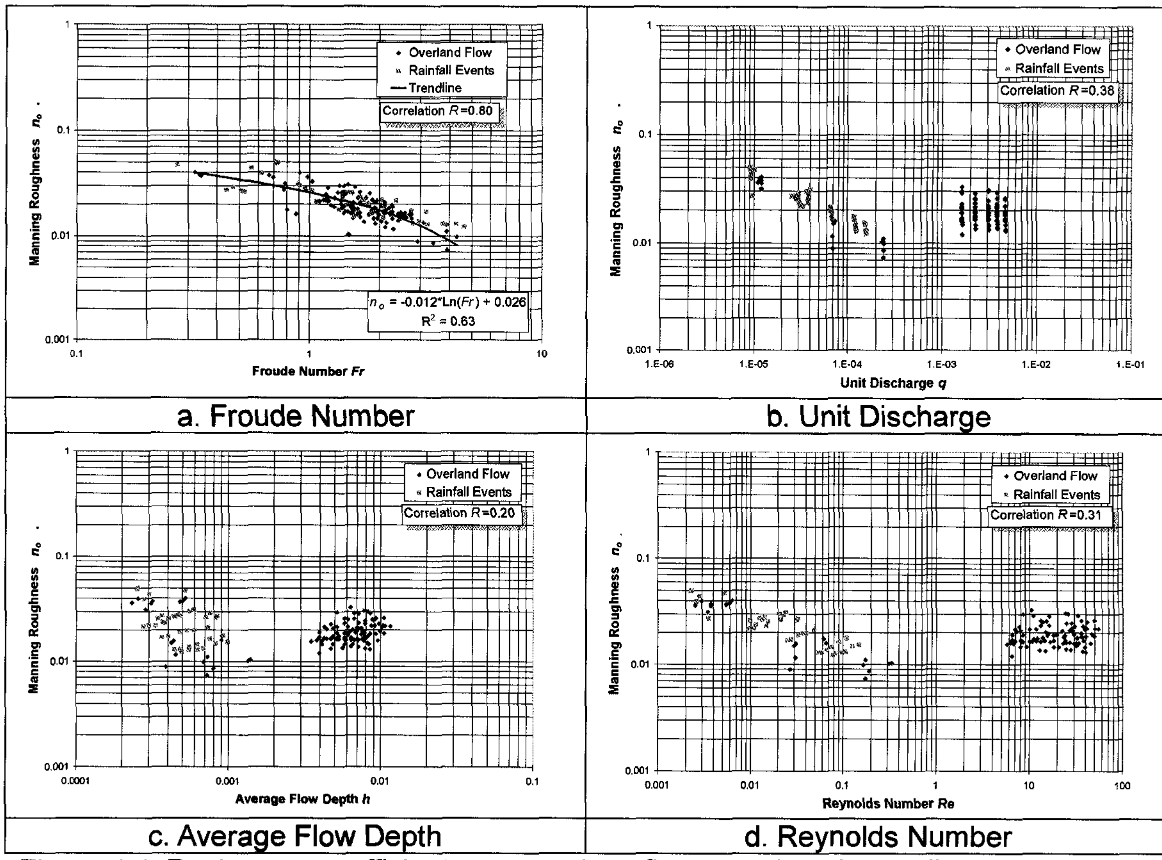


Figure 4.3. Resistance coefficient f to overland flow based on the published data used in this study.



a. Froude Number
b. Unit Discharge
c. Average Flow Depth
d. Reynolds Number

Figure 4.4. Resistance coefficient n_o to overland flow based on the published data used in this study.

In Fig. 4.4, the relationship of Manning n_o and Froude number Fr has the highest correlation among the relationships within Figs. 4.3 and 4.4 for sand particles. The trend line is

$$n_o = -0.012 \cdot \ln(Fr) + 0.026 \tag{4.17}$$

with a R^2 of 0.63. This means the gravity force is an important factor for overland flow.

According to the experimental data used in this study, overland flow includes sheet flow and rill flow. The properties of them were described in section 2.2. In practice, the pattern of rill network is difficult to predict because it varies with flow depth, soil type, vegetation, topography, etc. For most existing distributed hydrology models, the resolution of computation cells is much larger than rill size. For example, the most popular DEM resolutions published by USGS are 10 meters by 10 meters or 30 meters by 30 meters which are much wider than a rill width. For overland flow, average computations using in most existing hydrology models treat the flow in the computation cells as sheet flow. When the Manning equation is used to compute the average flow velocity, the Manning n_o is used as an average resistance coefficient for a computation cell. The factors included in the Manning n_o has been explained in section 3.4.1. This tells us that the calibration of the Manning n_o needs to be carried out for simulations using the distributed hydrology models.

In addition, the USLE crop management factor C is unity for bare soil surface. It is used in the soil erosion equations listed in Table 4.2. However, according to Figs. 4.3 and 4.4, those experimental data were measured from bare soil surfaces and show a wide range of flow resistance when unit discharge or slope is constant. Generally, overland flow soil transport capacity should be affected by flow resistance. It tells us the USLE factor C may not complete reflect the impact of flow resistance variation.

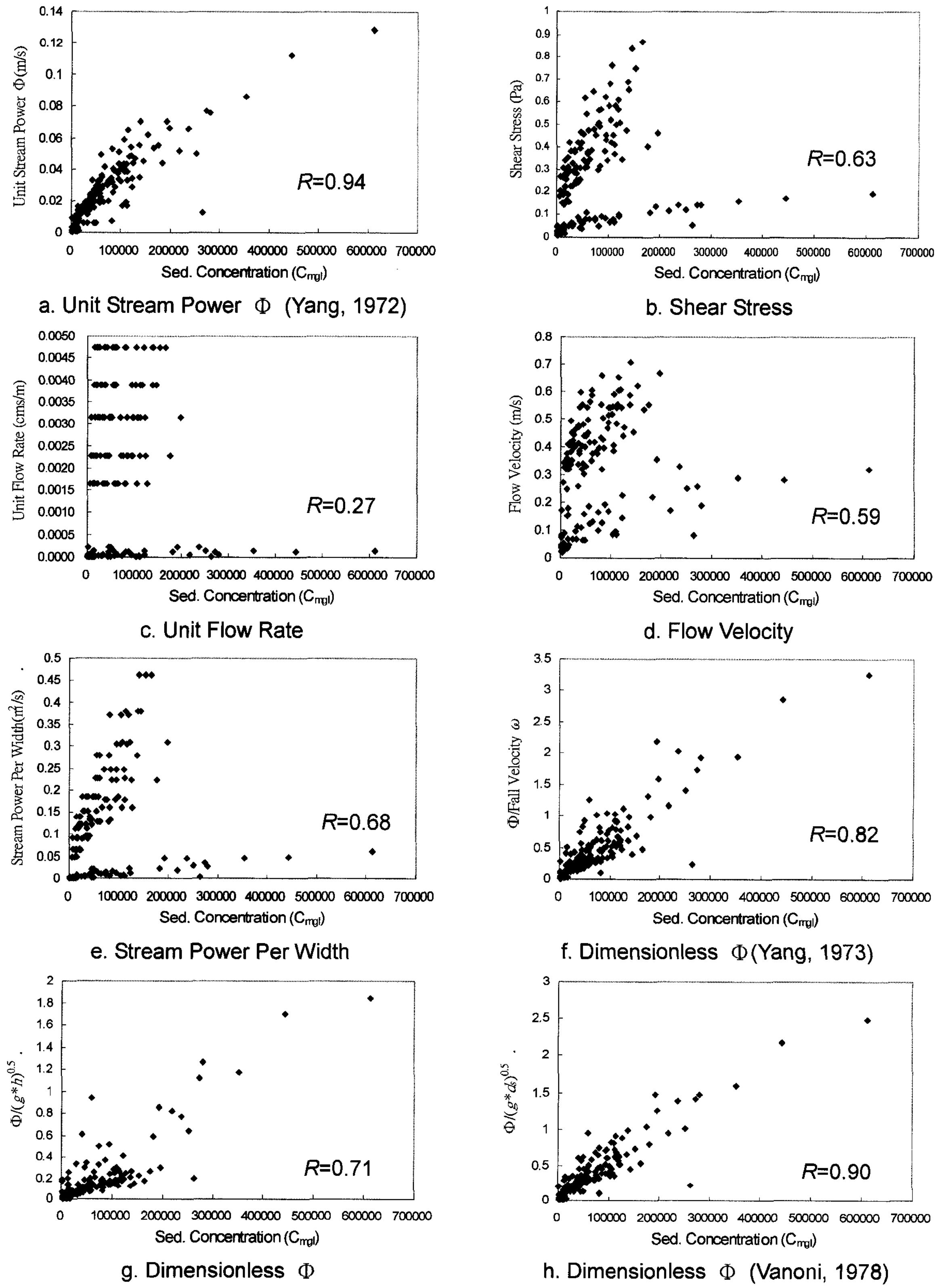
4.3 Determine the Most Significantly Dominant Variable

Referring to section 2.4.2, sediment concentration of overland flow is independent of unit flow discharge because flow discharge and sediment concentration have different tendencies in hydraulics. The following analyses are only for overland flow sediment concentration.

4.3.1 Relationship analysis among variables

First, we plot the relationship between observed sediment concentration and recommended dominant variables. These plots are shown in Fig. 4.5. The blue points are the observed data in this study. Among all the variables, the unit stream power has the strongest correlation with sediment concentration. Because of the lack of temperature record, a constant viscosity is assumed for the calculation of the particle fall velocity. This assumption may cause an error of up to 200% in the estimation of the particle fall velocity and also reduce the relationship with observed data on the plot when the fall velocity is used. Had the water temperature data been given, the dimensionless unit stream power might have a better correlation with sediment concentration. From practical point of view, water temperature varies with time and space in a watershed, and the dimensionless unit stream power is not suggested for use in this study.

Next, a correlation analysis is performed to verify the most significant variable. Including all of the suggested dominant factors from previous studies, the resulting correlations are shown in Table 4.6. The unit stream power Φ has the highest correlation with observed sediment concentrations C_s. The least significant variable is unit discharge with a correlation value of 0.27. This contradicts the traditional belief that unit discharge is a significant factor for overland flow erosion.



a. Unit Stream Power Φ (Yang, 1972)

b. Shear Stress

c. Unit Flow Rate

d. Flow Velocity

e. Stream Power Per Width

f. Dimensionless Φ (Yang, 1973)

g. Dimensionless Φ

h. Dimensionless Φ (Vanoni, 1978)

Note: R = correlation coefficient

Figure 4.5. Relationships between observed concentration and dominant variables

Table 4.6. Correlation table of relationships between observed dominant variables and sediment concentrations for overland flow

Correlations	C_s	q	V	Ψ	τ	Φ	Φ/ω	$\frac{\Phi}{\sqrt{gh}}$	$\frac{\Phi}{\sqrt{gd_s}}$
C_s	1	0.27	0.59	0.68	0.63	0.94	0.82	0.71	0.90
q	0.27	1	0.83	0.76	0.73	0.33	-0.03	-0.22	0.13
V	0.59	0.83	1	0.82	0.74	0.68	0.38	0.13	0.54
Ψ	0.68	0.76	0.82	1	0.95	0.76	0.29	0.14	0.50
τ	0.63	0.73	0.74	0.95	1	0.69	0.17	0.08	0.38
Φ	0.94	0.33	0.68	0.76	0.69	1	0.79	0.70	0.91
Φ/ω	0.82	-0.03	0.38	0.29	0.17	0.79	1	0.89	0.97
$\frac{\Phi}{\sqrt{gh}}$	0.71	-0.22	0.13	0.14	0.08	0.70	0.89	1	0.84
$\frac{\Phi}{\sqrt{gd_s}}$	0.90	0.13	0.54	0.50	0.38	0.91	0.97	0.84	1

4.3.2 Simple regression equations

In this study, laboratory data are used to test the goodness of fit of seven regression equations. Excluding the data collected during rainfall events, 116 sets of surface flow data are used to make simple regression analyses. Sediment concentration is treated as a dependent variable. The results and ranking based on their square of correlation coefficient R^2 are

$$C_{mgl} = 4684972.4(VS)^{1.217}, \quad R^2 = 0.879 \tag{4.18}$$

$$C_{mgl} = 19709844(qS)^{0.68}, \quad R^2 = 0.714 \tag{4.19}$$

$$C_{mgl} = 161366(\tau)^{1.11}, \quad R^2 = 0.680 \tag{4.20}$$

$$C_{mgl} = 172856.6(V)^{1.519}, \quad R^2 = 0.667 \tag{4.21}$$

$$C_{mgl} = 130081(\frac{VS}{\omega})^{1.022}, \quad R^2 = 0.661 \tag{4.22}$$

$$C_{mgl} = 1243153(q)^{0.554}, \quad R^2 = 0.458 \tag{4.23}$$

The above results show that Eq. (4.18) has the highest correlation with overland flow sediment concentration. Unit stream power is the most significant variable among all parameters. In addition, a regression equation based on Eq. (2.19) is obtained using laboratory data and shown as

$$C_{mgl} = 75844964 \cdot q^{0.4} S^{1.74}, \quad R^2 = 0.840 \tag{4.24}$$

The correlation square R^2 of Eq. (4.24) is 0.84 and is less than Eq. (4.18).

We can plot different best fit lines for the collected samples. In this study, 95% of observed sediment concentrations are less than 250,000 *mgl* (Fig. 4.6). In this section, a simple power function based on regression equations Eqs. (4.18) to (4.23) with a dominant variable may agree with observed laboratory data. However, the maximum sediment concentration is 1922,000 *mgl* for saturated sand clusters and is seven times over the maximum observed data. One of the primary objectives of this study is to develop an overland flow sediment transport equation with the consideration of the minimum and maximum concentration limits, which are zero *mgl* and 1922,000 *mgl*, respectively, for sand particles.

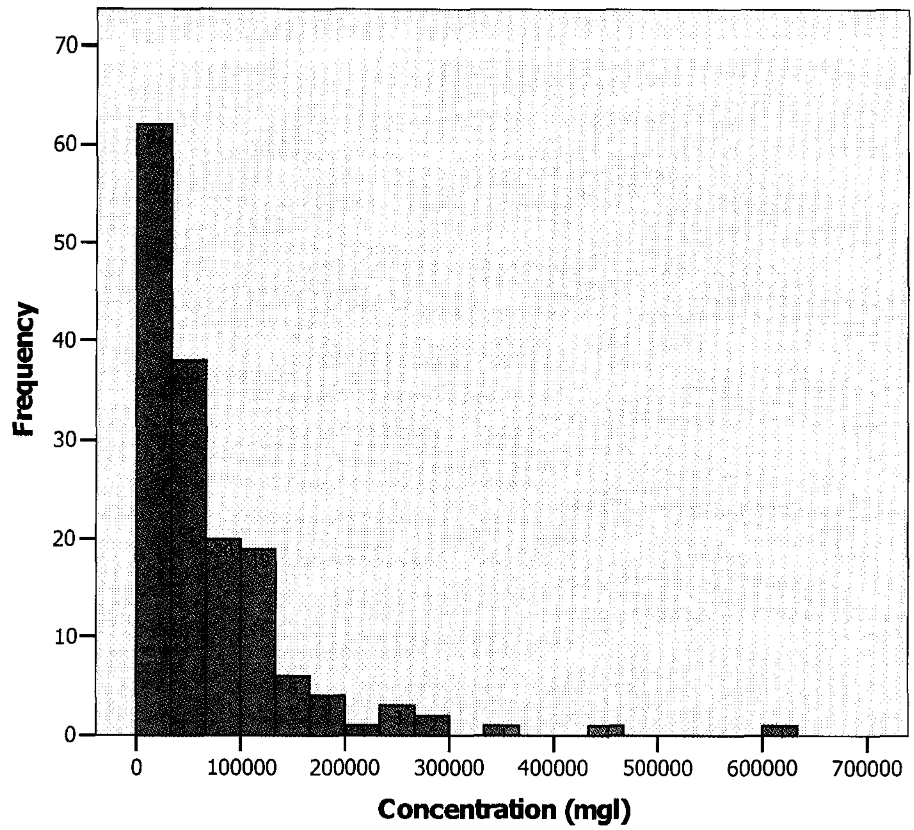


Figure 4.6. Histogram of experimental data distribution in this study

4.4 Maximum concentration limit and bounded exponential regression formula

A bounded exponential regression formula, the Weibull Function (Weibull 1951), can present bounded limits. The general formula of the Weibull Function is expressed as

$$Y = 1 - e^{-X} \tag{4.25}$$

where Y and X = variables. Then,

$$Y \to 1 \text{ when } X \to \infty \tag{4.26}$$

and

$$Y \to 0 \text{ when } X \to 0 \tag{4.27}$$

In this study, sediment concentration C_{mgl} is seen as the dependent variable Y and the power function of $a \cdot \Omega^b$ is used to represent the potential of sediment transport capacity and is the independent variable X. To consider sediment transport potential, and bounded limits of sediment concentrations, the following Weibull Function based regression formula is used to estimate the sediment transport capacity of overland flow.

$$C_{mgl} = C_{\max} \cdot \left(1 - e^{-a \cdot \Omega^b}\right) \quad (4.28)$$

where a and b = coefficients; and C_{max} = the maximum sediment concentration. For saturated sand particles, C_{max}=1922,000 *mgl*. This formula is a nonlinear function for the dominant variable Ω. The revised Weibull Function is shown as the green trend line in Fig. 4.7.

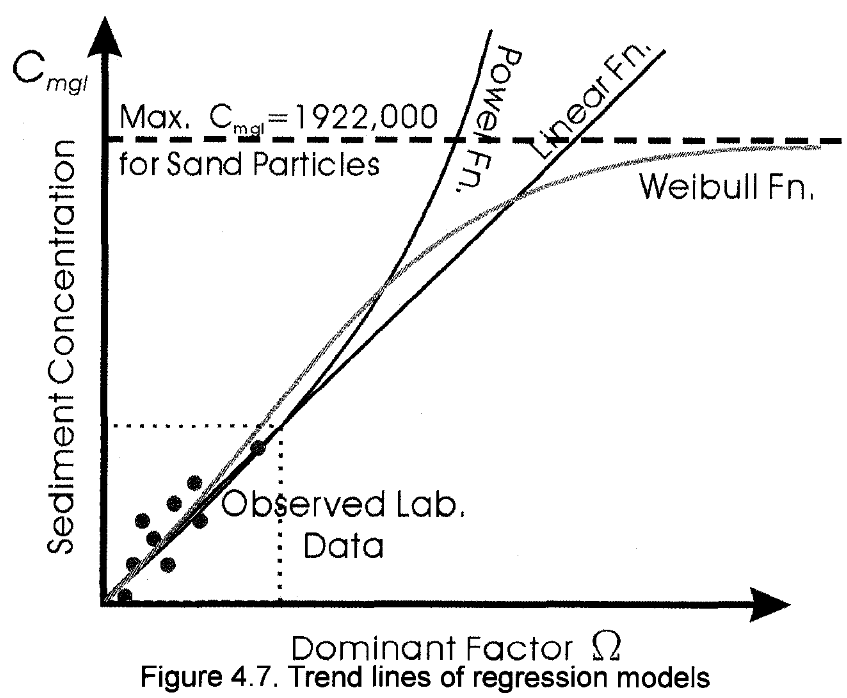


Figure 4.7. Trend lines of regression models

We re-do all of the simple regressions based on the proposed regression model and dominant variables. The results are

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-2.770 \cdot \Phi^{1.248}}\right), \quad R^2 = 0.880 \tag{4.29}$$

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-49.177 \cdot (qS)^{0.839}}\right), \quad R^2 = 0.455 \tag{4.30}$$

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-0.092 \cdot \tau^{0.997}}\right), \quad R^2 = 0.395 \tag{4.31}$$

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-0.266 \cdot S^{0.774}}\right), \quad R^2 = 0.0.376 \tag{4.32}$$

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-0.134 \cdot V^{1.687}}\right), \quad R^2 = 0.366 \tag{4.33}$$

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-0.111 \cdot q^{0.201}}\right), \quad R^2 = 0.091 \tag{4.34}$$

Eq. (4.29), which uses unit stream power as the dominant variable, has the highest R^2 of 0.88. Other R^2 values indicate that those regression equations cannot represent data very well when the maximum sediment concentration limit is included in the regression analyses. This means that these dominant factors can only represent conditions of low sediment concentration for overland flow. As sediment concentration increases, other physical factors may need to be included in the revised regression model. It should be noted that using unit stream power as the dominant factor produces the highest R^2 values in both the simple power function formula and the revised Weibull function formula.

4.5 Correlation and Regression Analyses

According to the results in sections 4.1, 4.3, and 4.4, using unit stream power Φ as the dominant variable has the best ability to estimate overland flow sediment concentration. In order to further improve results in Fig. 4.1, the parameters A and B in Eq. (4.2) need to be expressed as functions of important physical factors.

4.5.1 Important physical factors

A correlation analysis is used to determine the significance of physical parameters illustrated in Section 3.3. Excluding the data with rainfall events, the factors used in correlation analysis are sediment concentration C_s, particle size d_s, bed slope S, unit discharge q, flow depth h, flow velocity V, particle fall velocity ω, flow Reynolds number Re, grain shear Reynolds number Re_*, particle Reynolds number Re_p, Froude number Fr, and submergence h/d_s.

Table 4.7 shows the study results. It is apparent that Froude number has a higher correlation than all the Reynolds numbers because overland flow is a gravity flow. The correlation between slope and velocity is only -0.04, which is very weak. This means that slope and flow velocity are independent of each other. The correlations of particle size and relative submergence are weak. This means that particle roughness is not an important factor or that it is caused by a narrow range of particle size. Unit stream power has the highest correlation, followed by velocity and slope.

Variables with high correlation are chosen to represent their individual physical impact. Usually, when a correlation coefficient is greater than 0.5, the relationship is considered significant. In Table 4.7, slope, flow velocity and Froude number are significant factors from the observed data.

Rainfall intensity i, raindrop velocity V_i, rainfall power P_i, the ratio of rainfall intensity to flow velocity i/V, and the ratio of rainfall intensity to flow depth i/h, are used to determine the importance of factors associated with rainfall impacts. The comparison is summarized in Table 4.8. i/V has the highest correlation with rainfall impact.

Including the most significant dominant variable, the unit stream power Φ, and other important physical factors, sediment concentration can be expressed as

$$C_{mgl} = f(\Phi, Fr, V, S, i/V) \tag{4.35}$$

These important variables are used to develop an overland flow sediment transport equation based on the revised regression model, Eq. (4.28).

4.5.2 Physically based regression equations

In this study, unit stream power Φ has been shown as the most significant dominant variable. Eq. (4.28) can be expressed as

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-M \cdot \Phi^N}\right) \tag{4.36}$$

M and *N* are functions of other physical parameters. Gilbert (1914) showed that *M* increases linearly with increasing value of *N*. Hence, *M* and *N* can be expressed as

$$M = m_1 \cdot S + m_2 \cdot V + m_3 \cdot Fr + m_4 \tag{4.37}$$

$$N = n_1 \cdot S + n_2 \cdot V + n_3 \cdot Fr + n_4 \tag{4.38}$$

where m_i and n_i = coefficients.

Table 4.7. Correlation table of physically effective factors

	C_s	d_s	S	q	h	V	ω	Re	Re^*	Re_p	Fr	h/ds	VS
C_s	1	0.001	0.59	0.27	0.05	0.59	0.02	0.12	-0.01	0.26	0.70	0.13	0.94
d_s	0.001	1	-0.16	0.44	0.65	0.22	0.99	0.47	0.99	0.93	-0.29	-0.20	0.06
S	0.59	-0.16	1	-0.28	-0.44	-0.04	-0.19	-0.31	-0.14	-0.01	0.52	-0.39	0.59
q	0.27	0.44	-0.28	1	0.91	0.83	0.50	0.95	0.40	0.56	0.08	0.63	0.33
h	0.05	0.65	-0.44	0.91	1	0.65	0.69	0.91	0.61	0.66	-0.15	0.55	0.08
V	0.59	0.22	-0.04	0.83	0.65	1	0.30	0.64	0.16	0.39	0.52	0.62	0.68
ω	0.02	0.99	-0.19	0.50	0.69	0.30	1	0.51	0.97	0.93	-0.26	-0.15	0.10
Re	0.12	0.47	-0.31	0.95	0.91	0.64	0.51	1	0.45	0.56	-0.05	0.54	0.15
Re^*	-0.01	0.99	-0.14	0.40	0.61	0.16	0.97	0.45	1	0.93	-0.31	-0.23	0.04
Re_p	0.26	0.93	-0.01	0.56	0.66	0.39	0.93	0.56	0.93	1	-0.14	-0.11	0.31
Fr	0.70	-0.29	0.52	0.08	-0.15	0.52	-0.26	-0.05	-0.31	-0.14	1	0.13	0.75
h/d_s	0.13	-0.20	-0.39	0.63	0.55	0.62	-0.15	0.54	-0.23	-0.11	0.13	1	0.07
VS	0.94	0.06	0.59	0.33	0.08	0.68	0.10	0.15	0.04	0.31	0.75	0.07	1

Table 4.8. Correlation table of physical factors regarding rainfall impact

Correlations	C_s	i	V_i	P_i	i/V	i/h
C_s	1	-0.04	0.06	-0.07	-0.43	0.04
i	-0.04	1	0.97	1.00	0.73	0.81
V_i	0.06	0.97	1	0.96	0.64	0.77
P_i	-0.07	1.00	0.96	1	0.75	0.80
i/V	-0.43	0.73	0.64	0.75	1	0.52
i/h	0.04	0.81	0.77	0.80	0.52	1

Non-linear regression analysis is used to determine the coefficients of the proposed soil erosion formula, Eq. (4.36). The regression equation obtained by using surface flow data excluding rainfall events is

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-M \cdot \Phi^N}\right) \tag{4.39}$$

where

$$M = -0.654 \cdot S - 3.848 \cdot V + 0.227 \cdot Fr + 2.657 \tag{4.40}$$

$$N = -1.629 \cdot S - 1.170 \cdot V + 0.071 \cdot Fr + 1.532 \tag{4.41}$$

with $R^2 = 0.91$ for sediment data excluding rainfall data. $R^2 = 0.88$ for all 158 data sets, including rainfall data, used in this study. In Eqs. (4.39) to (4.41), V = flow velocity in *m/s*; and C_{mgl} = sediment concentration in *mgl*. The comparison between predicted values and observed data is shown in Fig. 4.8.

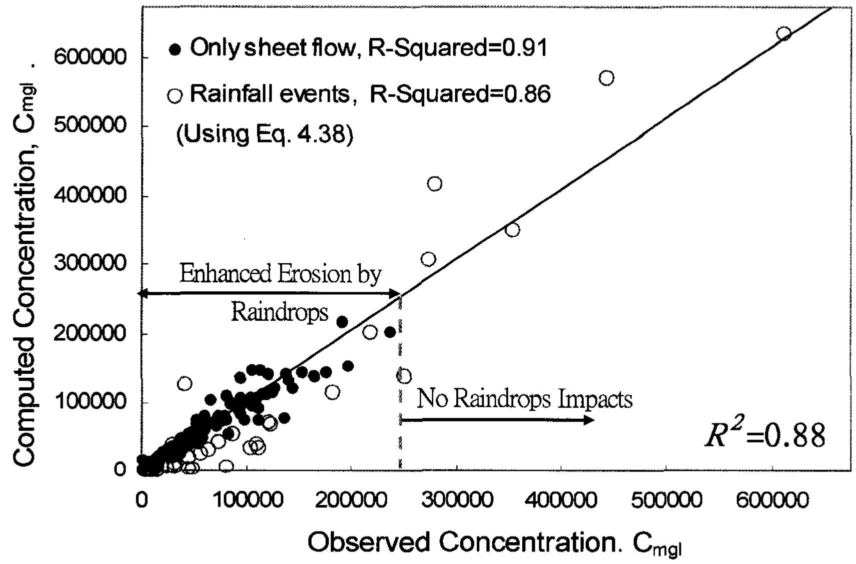


Figure 4.8. Agreements between the non-linear regression equation, Eq.(4.38), and data.

Raindrops can complicate the relationship between surface erosion rate and unit stream power. Excluding rainfall data, the predicted values of concentration and unit stream power have good agreements with observed data, as shown in Fig. 4.8. However, the comparison shows under estimations when the observed concentration of simulation rainfall events is less than about 260,000 *mgl*. This results from the raindrop erosion enhancement. This shows a need to modify Eq. (4.39) to consider the impact due to raindrops. Guy et al. (1990) suggested to add a rainfall enhancement term in the overland flow sediment transport equation.

An erosion enhancement term *I* is used in this study to represent the rainfall impact of overland flow erosion. The regression equation is expressed as

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-\left(M \cdot \Phi^{N}\right) I}\right) \tag{4.42}$$

where

$$M = -0.654 \cdot S - 3.848 \cdot V + 0.227 \cdot Fr + 2.657 \tag{4.43}$$

$$N = -1.629 \cdot S - 1.170 \cdot V + 0.071 \cdot Fr + 1.532 \tag{4.44}$$

$$I = \left[1 + 1.141 \cdot (1 - e^{-0.005\left(10^{4} \cdot \frac{i}{V}\right)^{23.012}}) \right] \tag{4.45}$$

, *i* = rainfall intensity in *m/s*, and is with a $R^2 = 0.91$ for simulation rainfall events, and also a $R^2 = 0.91$ for all 158 data sets used in the study. This means that using a rainfall enhancement term in Eq. (4.42) can increase the accuracy of overland flow sediment concentration predictions.

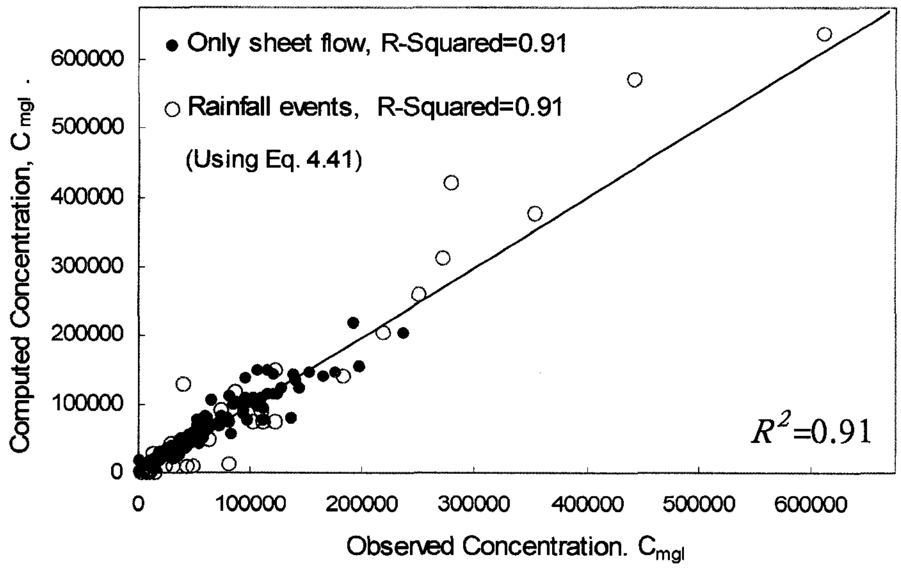


Figure 4.9. Agreements between the non-linear regression equation, Eq.(4.41), and data.

Figs. 4.8 and 4.9 show good agreements between predicted and observed sediment concentrations. A regression equation with a value of R^2 greater than 0.8 is considered to be a good regression result. Both regression equations, Eqs. (4.39) and (4.42), have high R^2 values.

When the 158 sets of published data are used as inputs into Eq. 4.42, the value range of M, N and I terms are

$$M = 0.5 \sim 2.64 \tag{4.46}$$

$$N = 0.74 \sim 1.5 \tag{4.47}$$

$$I = 1 \sim 2.14 \tag{4.48}$$

This shows that raindrops can increase a maximum of 2.14 times of sediment concentration among the published data used in this study.

4.5.3 Sensitivity analysis

Sensitivity analyses of the developed model are performed by changing the values of each input variable to a range from -60% to 60%. The variations of predicted concentration versus input variables are listed in Table 4.9 and plotted in Fig. 4.10. For example, increasing input slope by 10% will result in a 6.9% increase of predicted concentration. Excluding the consideration of rainfall impact, the analysis shows that unit stream power has the steepest slope on the plot and is the most sensitive variable in the model for sediment concentration. The sensitivity analyses results support the idea that the unit stream power is the dominant factor for overland erosion studies. Slope, flow velocity, and Froude number are other sensitive variables. Rainfall only impacts the overland flow sediment transport capacity at high rainfall intensity, slow flow velocity, or low sediment concentration. This analysis shows that gravity is the significant driving force for overland flow, and the unit stream power dominates sediment concentration.

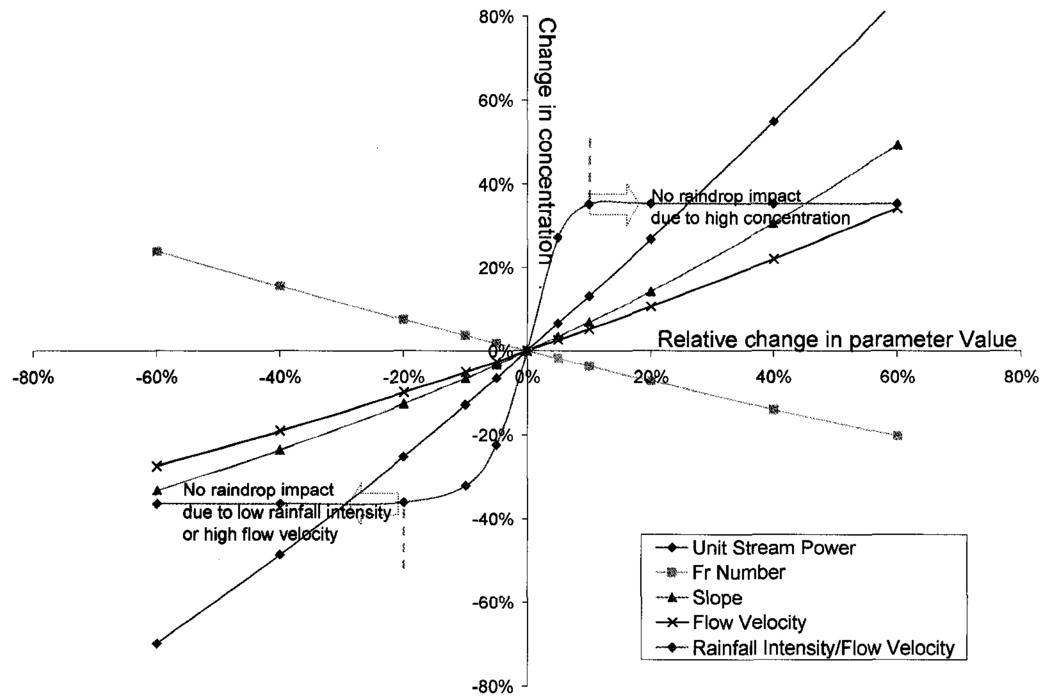


Figure 4.10. Plot of sensitivity analysis

Table 4.9. Comparison of sensitivity analysis results

Change of Variable	Variation of Predicted Concentration Based on Variables				
	Φ	S	V	Fr	i/V
-60%	-69.7%	-33.1%	-27.3%	23.9%	-36.4%
-40%	-48.6%	-23.5%	-19.0%	15.5%	-36.4%
-20%	-25.2%	-12.5%	-9.9%	7.6%	-36.1%
-10%	-12.8%	-6.5%	-5.0%	3.7%	-32.1%
-5%	-6.5%	-3.3%	-2.5%	1.9%	-22.4%
0%	0.0%	0.0%	0.0%	0.0%	0.0%
5%	6.6%	3.4%	2.6%	-1.8%	27.1%
10%	13.2%	6.9%	5.2%	-3.6%	35.2%
20%	26.8%	14.3%	10.7%	-7.1%	35.3%
40%	54.8%	30.7%	22.1%	-13.9%	35.3%
60%	84.1%	49.4%	34.3%	-20.2%	35.3%

4.5.4 Applicability of the developed soil erosion equation for overland flow

The developed soil erosion equation, Eq. (4.42), shows a good agreement with published laboratory data using unit stream power as the dominant variable. Many of distributed hydrology models treat overland flow as turbulent flow and use the Manning equation to represent flow resistance. Based on using the Manning equation, the unit stream power, flow velocity and Froude number in Eq. (4.42) can be expressed in a function of q and S. They are

$$V \cdot S \sim q^{0.4} S^{1..3} \tag{4.49}$$

$$S \sim q^{0.0} S^{1.0} \tag{4.50}$$

$$V \sim q^{0.4} S^{0.3} \tag{4.51}$$

$$Fr \sim q^{0.1} S^{0.45} \tag{4.52}$$

The erosion potential term, $M \cdot \Phi^N$,in Eq. (4.42) can be transformed into q and S formulas and shown as a coverage on a ε versus β plot (Fig. 4.1). For each data set j, the erosion potential term is expressed as

$$M_j \cdot \Phi^{N_j} \sim q^{\varepsilon_j} S^{\beta_j} \tag{4.53}$$

The effective coverage can be expressed by using the values of ε_j and β_j from the data used in this study. M_j is a function of slope S, velocity V, and Froude Fr. The computed erosion potential term $M \cdot \Phi^N$ can be treated as the combination of $S \cdot \Phi^N$, $V \cdot \Phi^N$, and $Fr \cdot \Phi^N$. Based on Eqs (4.49) to (4.53) and Eq. (4.42), ε_i and β_i can be computed from

Term (S, VS):

$$\varepsilon_i = N_j \cdot 0.4 + 0.0 \tag{4.54}$$

$$\beta_i = N_j \cdot 1.3 + 1.0 \tag{4.55}$$

Term (*V, VS*):

$$\varepsilon_i = N_j \cdot 0.4 + 0.4 \tag{4.56}$$

$$\beta_i = N_j \cdot 1.3 + 0.3 \tag{4.57}$$

Term (*Fr, VS*):

$$\varepsilon_i = N_j \cdot 0.4 + 0.1 \tag{4.58}$$

$$\beta_i = N_j \cdot 1.3 + 0.45 \tag{4.59}$$

Based on sediment concentration data used in this study, the effective coverage of Eq. (4.42) is shown as an enclosed area in Fig. 4.11. It covers a large part of empirical studies.

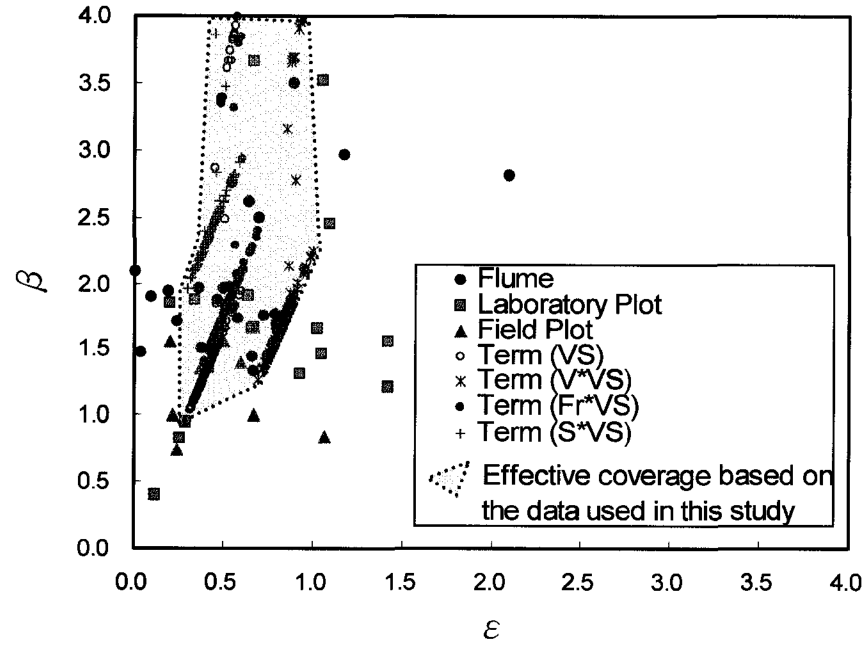


Figure 4.11. Effective coverage of sediment concentration data used in this study using Eq. (4.41)

Based on conclusions of Julien and Simons (1985), there is a good applicability of using Eq. (4.42) for overland flow erosion estimation because the enclosed area covers a large part of empirical coefficients, including sheet/interrill flow and rill flow, as determined in the previous section.

CHAPTER V MODEL TEST USING ONE DIMENSIONAL OVERLAND FLOW EROSION SIMULATION

The main objective of this chapter is to calibrate the developed regression equations from chapter four. Regarding sediment yield simulation, both overland flow and channel flow routing are included in existing spatially distributed watershed models. In order to exclude the effects from channel routing for simulation results, a one-dimensional overland flow routing is developed to simulate sediment transport on the soil surface and to validate the surface erosion equation developed in this study.

5.1 Experimental Field Data

Field experimental data collected by Barfield et al. (1983) are used to calibrate the regression equations developed in this study. Field erosion experiments were done on an area of 4.6 m by 22.1 m on 9 percent slope in Western Kentucky. The soil materials include topsoil, subsoil and shale. The observed hydrograph and sediment graph of seven experimental runs are used to compare with simulated results. Table 5.1 summarizes the field test conditions, soil material and suggested soil erodibility factor values used in their field experiments.

Table 5.1. Summary of field experiment runs (Barfield et al, 1983)

Run No.	Bed Material	Rainfall Intensity (mm/hr)	Rainfall Duration (min)	d_{50} (mm)	Soil Yield Per Unit Width (g/m)	Soil Erodibility Factor, K (tons/acre)
P33231	Tilled & wet topsoil	66	30	0.06	5577.78	0.437
P33131		61			4203.67	0.388
P32131	Tilled & wet subsoil	66		0.04	8829.77	0.527
P32231		66			4846.85	0.371
P32331		66			4342.51	0.256
P31131	Tilled & wet shale	61		0.05	1011.25	0.148
P31231		61			893.04	0.126

5.2 Numerical scheme of diffusive wave routing

A one dimensional (1-D) diffusive wave routing model is developed to simulate hydrologic condition and predict soil erosion or yield. The 1-D diffusive wave equation of overland flow is a partial differential equation

$$\frac{\partial h}{\partial t} + c_d \frac{\partial h}{\partial x} - D_d \frac{\partial^2 h}{\partial x^2} = (i - f) \tag{5.1}$$

where $c_d = \beta V$; $D_d = \frac{q}{2S}$; t = time; f_i = soil infiltration rate; and x = distance. If Manning's equation is used to represent flow resistance, then β = 5/3, $V = \frac{1}{n_o} h^{2/3} \sqrt{S_f}$, $S_f = S - \frac{\partial h}{\partial x}$ and n_o = Manning roughness coefficient. Numerical solution of the 1-D diffusive wave can be obtained by using the MacCormack scheme (MacCormack, 1971).

In the MacCormack scheme, the derivative operator is the average of the forward and backward operators such that

$$h = \frac{h^* + h^{**}}{2} \tag{5.2}$$

where h = predicted flow depth, and h^*, h^{**} = one-sided forward and backward differences, respectively. Eq. (5.2) can be approximated by a forward difference in time and in space (FTFS) to give predictor step

$$\frac{h_n^* - h_n^j}{\Delta t} + c_d \frac{h_{n+1}^j - h_n^j}{\Delta x} - (D_d + D_{num}) \frac{h_{n+1}^j - 2h_n^j + h_{n-1}^j}{\Delta x^2} = (i - f_i)_n^j \tag{5.3}$$

By multiplying with Δt,

$$h_n^* = h_n^j - \frac{c_d \Delta t}{\Delta x}\left(h_{n+1}^j - h_n^j\right) + (D_d + D_{num})\frac{\Delta t}{\Delta x^2}\left(h_{n+1}^j - 2h_n^j + h_{n-1}^j\right) + (i - f_i)_n^j \Delta t \tag{5.4}$$

where Δt = time step; Δx = distance step; j = simulation time; n = simulation location; and D_{num} = the truncation error of the advection scheme includes a numerical diffusion term (Julien, 2002), and

$$D_d + D_{num} = \frac{Vh}{2S_e} + \left(\frac{-c_d{}^2 \Delta t}{2} + \frac{c_d \Delta x}{2}\right) \tag{5.5}$$

Similarly, Eq. (5.2) can be approximated by a backward difference in time and in space (BTBS) to give the corrector step

$$\frac{h_n^{**} - h_n^*}{\Delta t} + c_d \frac{h_n^* - h_{n-1}^*}{\Delta x} - (D_d + D_{num}) \frac{h_{n+1}^* - 2h_n^* + h_{n-1}^*}{\Delta x^2} = (i - f_i)_n^* \tag{5.6}$$

By multiplying with Δt,

$$h_n^{**} = h_n^* - \frac{c_d \Delta t}{\Delta x}\left(h_n^* - h_{n-1}^*\right) + (D_d + D_{num})\frac{\Delta t}{\Delta x^2}\left(h_{n+1}^* - 2h_n^* + h_{n-1}^*\right) + (i - f_i)_n^* \Delta t \tag{5.7}$$

The Courant number, $C_c = \frac{c_d \Delta t}{\Delta x} = \frac{5}{3} V \frac{\Delta t}{\Delta x}$, will be used to check the numerical scheme stability. The MacCormack scheme is stable if the Courant-Friedrich-Levy (CFL) condition is less than or equal to 1 ($C_c \leq 1$).

5.3 Practical Application and Dimensionless Soil Erodibility Factors *K'*

For soil surface, soil erosion or yield can be expressed as

$$\text{Soil Yield} = f(\text{Erosivity}, \text{Erodibility}) \tag{5.8}$$

From section 4.5.2, Eq. (4.42) can be used to estimate soil yield for sand material with the consideration of flow resistance. The equation can compute overland flow sediment transport capacities with varying flow conditions. In this study, erodibility of soil yield is assumed from flow resistance and soil erodibility. The Manning equation is used to describe the flow resistance. A USLE erodibility factor K (tons/acre) is commonly used to indicate soil supply limit from bed. For practical purposes, a representative erodibility is needed for the overland flow sediment transport equation developed in this study. The representative erodibility, K_s, of the equation developed, Eq. (4.42), is determined from using field data of Barfield et al. (1983). The K_s value is 0.1 tons/acre, which is close to the commonly recommended value for fine sand (Julien, 2002). In order to apply the equations developed from this study, the following dimensionless soil erodibility factor K' is used

$$K' = \frac{K}{K_S} = \frac{K}{0.1} \tag{5.9}$$

An equation for the computation of overland sediment discharge in this study can be expressed as

$$q_s = q \cdot C_{mgl} \cdot K' \tag{5.10}$$

where,

$$C_{mgl} = 1922000 \cdot \left(1 - e^{-\left(M \cdot \Phi^N\right) I}\right) \tag{5.11}$$

$$\Phi = VS \tag{5.12}$$

$$M = -0.654 \cdot S - 3.848 \cdot V + 0.227 \cdot Fr + 2.657 \tag{5.13}$$

$$N = -1.692 \cdot S - 1.170 \cdot V + 0.071 \cdot Fr + 1.532 \tag{5.14}$$

$$I = \left[1 + 1.141 \cdot (1 - e^{-0.005\left(10^4 \cdot \frac{i}{V}\right)^{23.012}}) \right] \tag{5.15}$$

$$K' = \frac{K}{0.1} \tag{5.16}$$

where q_s = sediment transport rate per unit width in *g/sec/m*; q = unit discharge in m^3/m^2; V = flow velocity in *m/s*; i = rainfall intensity in m/s; and C_{mgl} = sediment concentration in *mgl*.

5.4 Comparison between Observed Data and Predicted Results

5.4.1 Parameters calibration

Manning coefficient n_o and mean infiltration rate f_i are inputs required in the 1-D overland flow model developed in this study. The hydrographs have been measured in Barfield et al. (1983) experimental runs. Consequently, the 1-D overland flow model was calibrated by adjusting the Manning's n_o and mean infiltration rate f_i for the seven experimental runs. During this process, each parameter is varied following a trial and error procedure, with all other parameters being constant. When the relative error in estimations of flow volume and time to concentration are less than 10%, the calibrated values are considered acceptable. Fig. 5.1 shows the calibrations of Manning's n_o for four experimental runs. The calibration results are listed in Table 5.2.

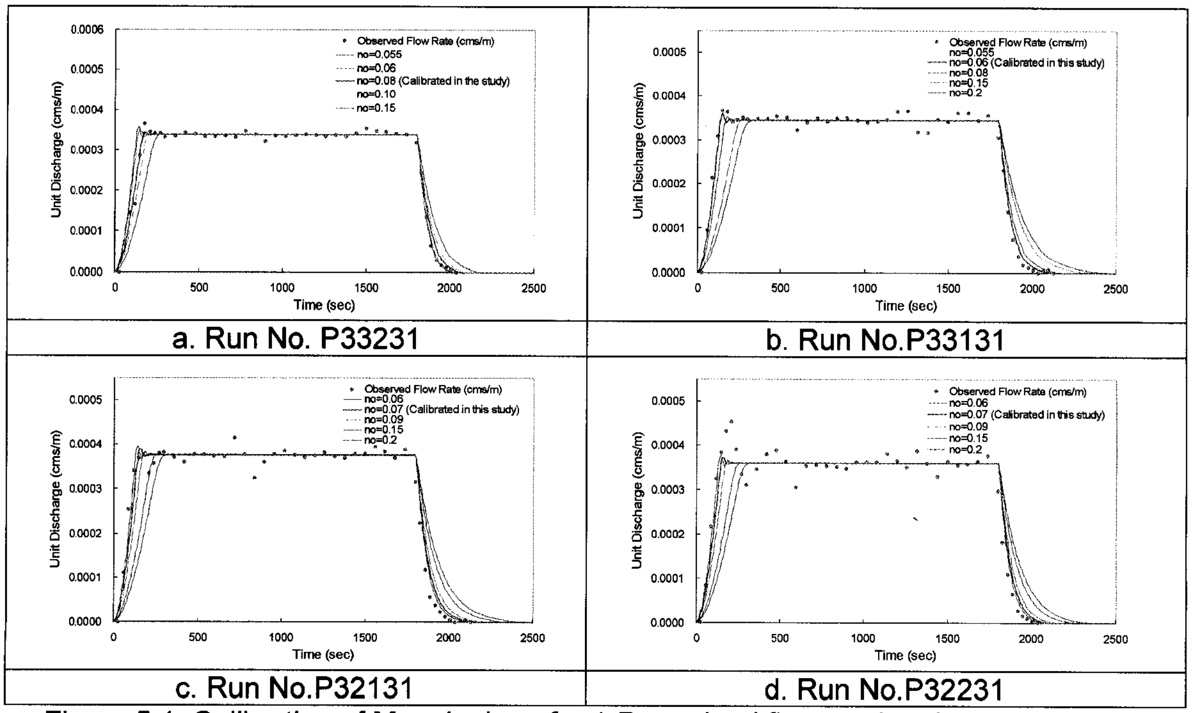


Figure 5.1. Calibration of Manning's n_o for 1-D overland flow routing developed in this study

Table 5.2. Calibrated Manning's n_o and average infiltration rate f_i.

Run No.	Manning n_o	Average infiltration rate, f_i (mm/hr)
P33231	0.08	10.5
P33131	0.06	4.5
P32131	0.07	4.5
P32231	0.07	7.1
P32331	0.07	7.1
P31131	0.14	2.0
P31231	0.18	8.5

5.4.2 Simulations of sediment transport

The given experimental field information, calibrated Manning roughness, and average infiltration rate which are used in the numerical simulations. Field experimental runs are used to test the overland flow 1-D diffusive model and the soil erosion equations, from Eq. (5.10) to Eq. (5.16), developed in this study. In addition, the overland flow soil transport capacity equation (Eq. 2.38) used in CASC2D-SED is also used to compute soil transport rate and compare with the predicted results using the equations developed in this study. In these simulations, USLE factors *C* and *P* are unity as Eq. (2.38) are used.

The simulation results and observed data are plotted in Figs. 5.2 to 5.8, with good agreements between predicted value and observed data. The simulations using Eq. (2.38) have over-estimations by comparing to observed data.

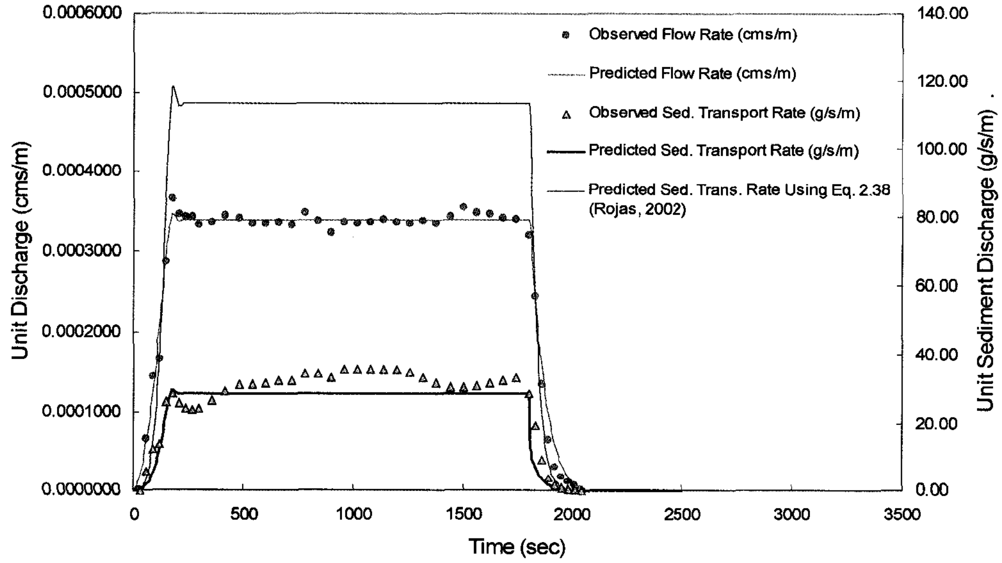


Figure 5.2. Comparison between predicted results and observed data for Run No. P33231.

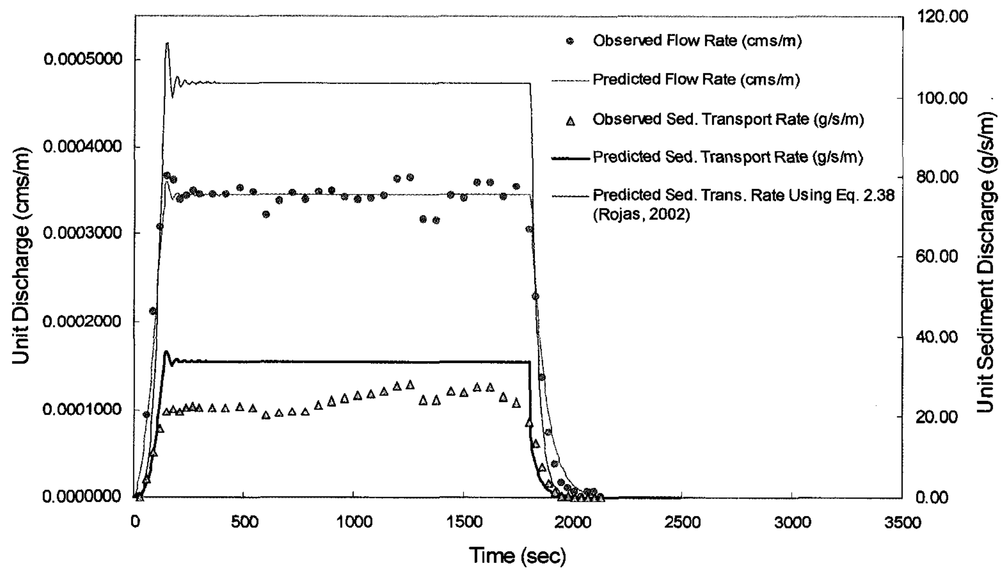


Figure 5.3. Comparison between predicted results and observed data for Run No. P33131.

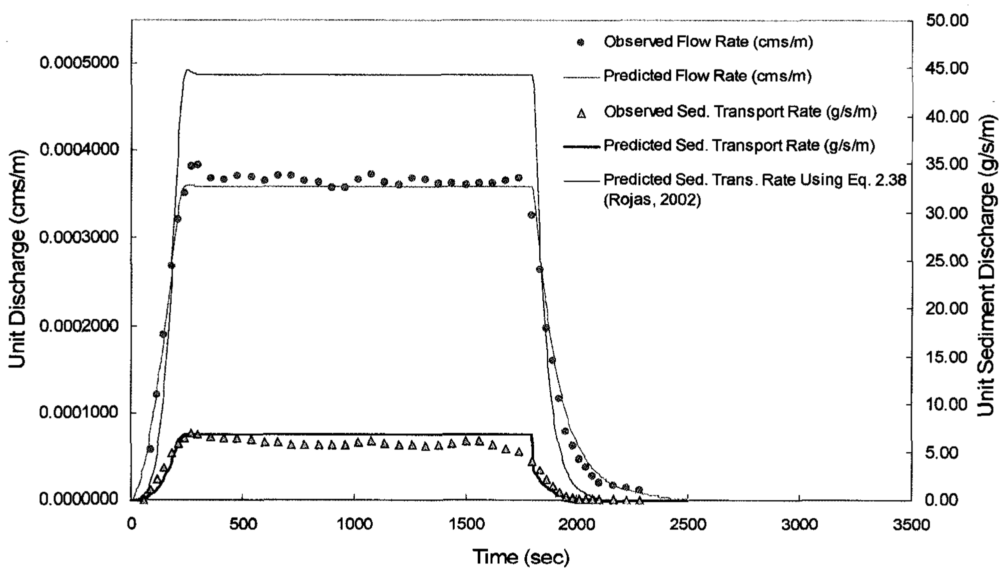


Figure 5.4. Comparison between predicted results and observed data for Run No. P31131.

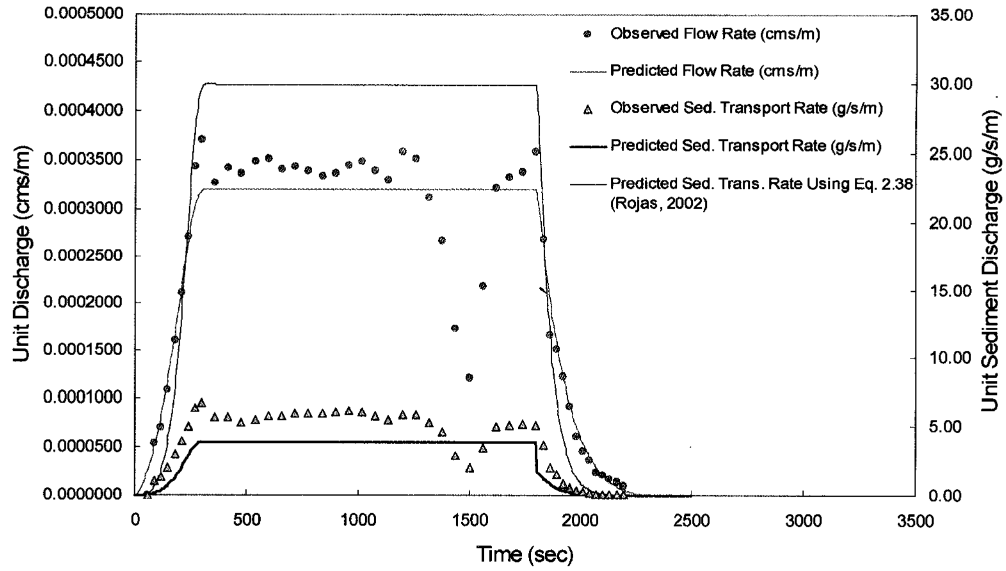


Figure 5.5. Comparison between predicted results and observed data for Run No. P31231

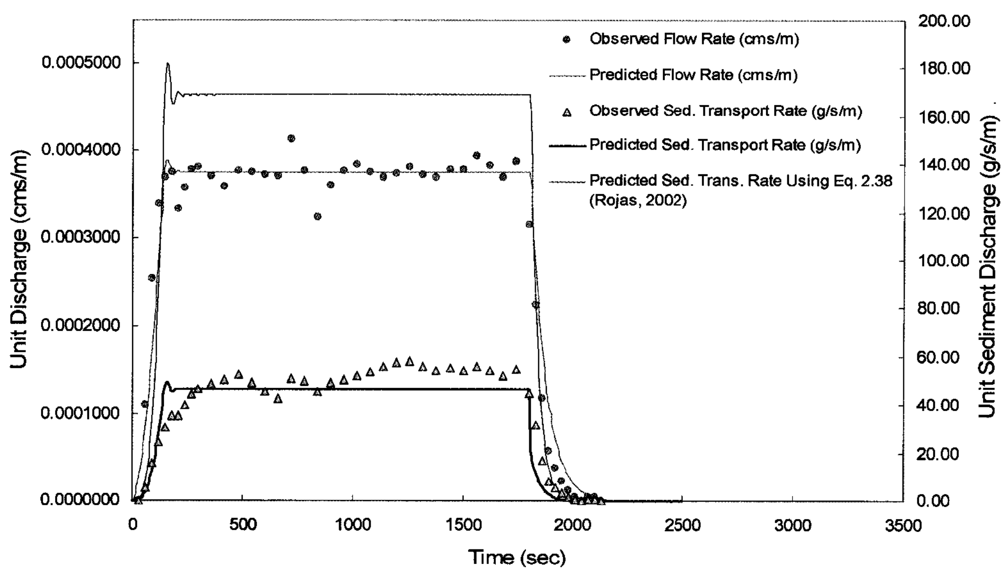


Figure 5.6. Comparison between predicted results and observed data for Run No. P32131.

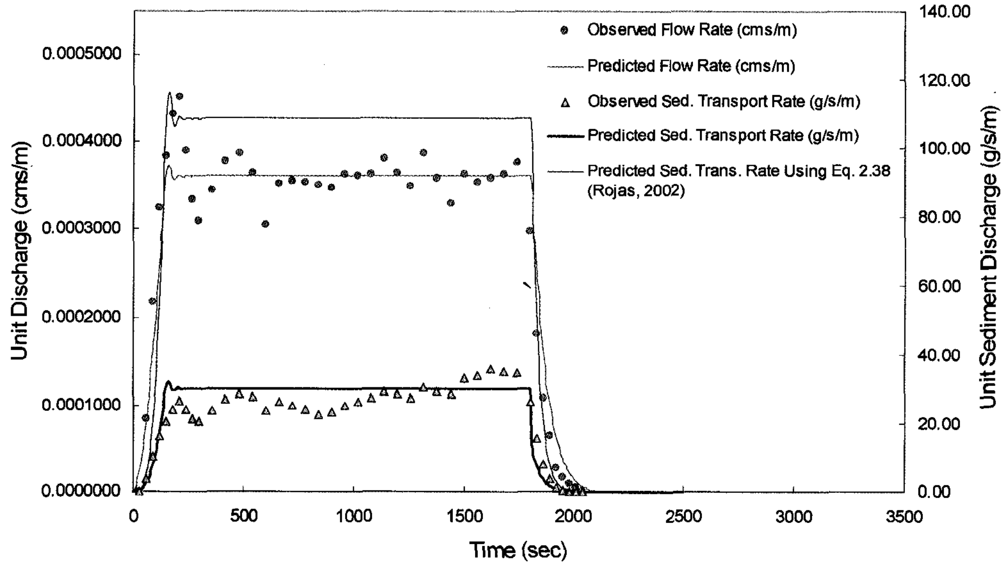


Figure 5.7. Comparison between predicted results and observed data for Run No. P32231

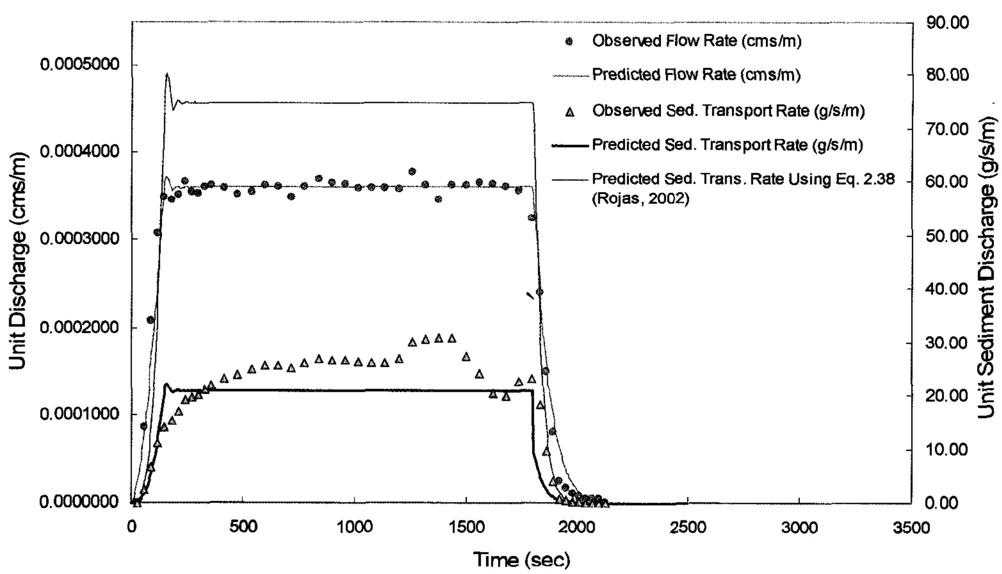


Figure 5.8. Comparison between predicted results and observed data for Run No. P32331

According to the simulation results, the maximum C_c values from simulated runs are within 0.40 to 0.79 (Table 5.3). This means that the routing model is stable because $C_c < 1$. The 1-D overland flow scheme and the developed soil erosion equation can represent soil erosion processes of overland flow very well.

Table 5.3. Values of Courant number C_c from numerical simulation.

Run No.	Courant number C_c
P33231	0.66
P33131	0.79
P32131	0.75
P32231	0.74
P32331	0.74
P31131	0.48
P31231	0.40

5.4.3 Comparison of predicted total soil yields

By accumulating the products of time period and soil transport rate, the total soil yield of each experimental run can be obtained. In addition, the Modified Universal Soil-Loss Equation (MUSLE) is also an event-based soil erosion model and can estimate total soil yield for a storm event. It is shown in Eq. (2.37). The estimations of soil yield using the MUSLE were used to compare with the estimations by using the soil erosion equation developed in this study and by using Eq. (2.38).

The input values of MUSLE factors and predicted soil yields are listed in Table 5.4. Based on the field plot with a 9% slope and 22.1m length, and Table 5.5, the unity value is used for the MUSLE factor *LS*. The predicted total soil yields by using different equations and comparison are shown in Table 5.6 and Fig. 5.9. The results show that using the equation developed in this study and using MUSLE have good agreement with observed data.

Table 5.4. Calculation table of using MUSLE for the experimental runs.

RUN	Q_v ac-ft	Q_p cfs	*K*	*LS*	*C*	*P*	*Predicted Total Soil Yield (kg)*
P33231	0.0022	0.0595	0.437	1	1	1	251.99
P33131	0.0023	0.0596	0.388	1	1	1	229.59
P32131	0.0025	0.0672	0.527	1	1	1	349.46
P32231	0.0024	0.0735	0.371	1	1	1	252.83
P32331	0.0024	0.0614	0.256	1	1	1	157.74
P31131	0.0024	0.0624	0.148	1	1	1	92.02
P31231	0.0021	0.0603	0.126	1	1	1	71.32

Table 5.5. Values for Topographic Factor, *LS*, for Moderate Ratio of Rill to Interrill Erosion (Renard et al., 1991).

	Horizontal Slope Length (ft.)																
Slope (%)	**<3**	**6**	**9**	**12**	**15**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**400**	**600**	**800**	**1,000**
0.2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06
0.5	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10
1.0	0.11	0.11	0.11	0.11	0.11	0.12	0.13	0.14	0.14	0.15	0.16	0.17	0.17	0.18	0.19	0.20	0.20
2.0	0.17	0.17	0.17	0.17	0.17	0.19	0.22	0.25	0.27	0.29	0.31	0.33	0.35	0.37	0.41	0.44	0.47
3.0	0.22	0.22	0.22	0.22	0.22	0.25	0.32	0.36	0.39	0.44	0.48	0.52	0.55	0.60	0.68	0.75	0.80
4.0	0.26	0.26	0.26	0.26	0.26	0.31	0.40	0.47	0.52	0.60	0.67	0.72	0.77	0.86	0.99	1.10	1.19
5.0	0.30	0.30	0.30	0.30	0.30	0.37	0.49	0.58	0.65	0.76	0.85	0.93	1.01	1.13	1.33	1.49	1.63
6.0	0.34	0.34	0.34	0.34	0.34	0.43	0.56	0.69	0.78	0.93	1.05	1.16	1.25	1.42	1.69	1.91	2.11
8.0	0.42	0.42	0.42	0.42	0.42	0.53	0.74	0.91	1.04	1.26	1.45	1.62	1.77	2.03	2.47	2.83	3.15
10.0	0.46	0.48	0.50	0.51	0.52	0.67	0.97	1.19	1.38	1.71	1.98	2.22	2.44	2.84	3.50	4.06	4.56
12.0	0.47	0.53	0.58	0.61	0.64	0.84	1.23	1.53	1.79	2.23	2.61	2.95	3.26	3.81	4.75	5.56	6.28
14.0	0.48	0.58	0.65	0.70	0.75	1.00	1.48	1.86	2.19	2.76	3.25	3.69	4.09	4.82	6.07	7.15	8.11
16.0	0.49	0.63	0.72	0.79	0.85	1.15	1.73	2.20	2.60	3.30	3.90	4.45	4.95	5.86	7.43	8.79	10.02
20.0	0.52	0.71	0.85	0.96	1.06	1.45	2.22	2.85	3.40	4.36	5.21	5.97	6.68	7.97	10.23	12.20	13.99
25.0	0.56	0.80	1.00	1.16	1.30	1.81	2.82	3.65	4.39	5.69	6.85	7.88	8.86	10.65	13.80	16.58	19.13
30.0	0.59	0.89	1.13	1.34	1.53	2.15	3.39	4.42	5.34	6.98	8.43	9.76	11.01	13.30	17.37	20.99	24.31
40.0	0.65	1.05	1.38	1.68	1.95	2.77	4.45	5.87	7.14	9.43	11.47	13.37	15.14	18.43	24.32	29.60	34.48
50.0	0.71	1.18	1.59	1.97	2.32	3.32	5.40	7.17	8.78	11.66	14.26	16.67	18.94	23.17	30.78	37.65	44.02
60.0	0.76	1.30	1.78	2.23	2.65	3.81	6.24	8.33	10.23	13.65	16.76	19.64	22.36	27.45	36.63	44.96	52.70

Table 5.6. Observed Sediment yields and predicted values

Run	Observed Soil Yield (kg)	Predicted Soil Yield (kg)		
		This Study	Eq. 2.38	MUSLE
P33231	256.58	226.92	894.11	251.99
P33131	193.37	267.54	825.75	229.59
P32131	406.33	368.74	1344.04	349.46
P32231	222.96	240.58	862.74	252.83
P32331	199.76	166.00	595.31	157.74
P31131	47.15	52.48	345.16	92.02
P31231	41.85	29.17	227.58	71.32

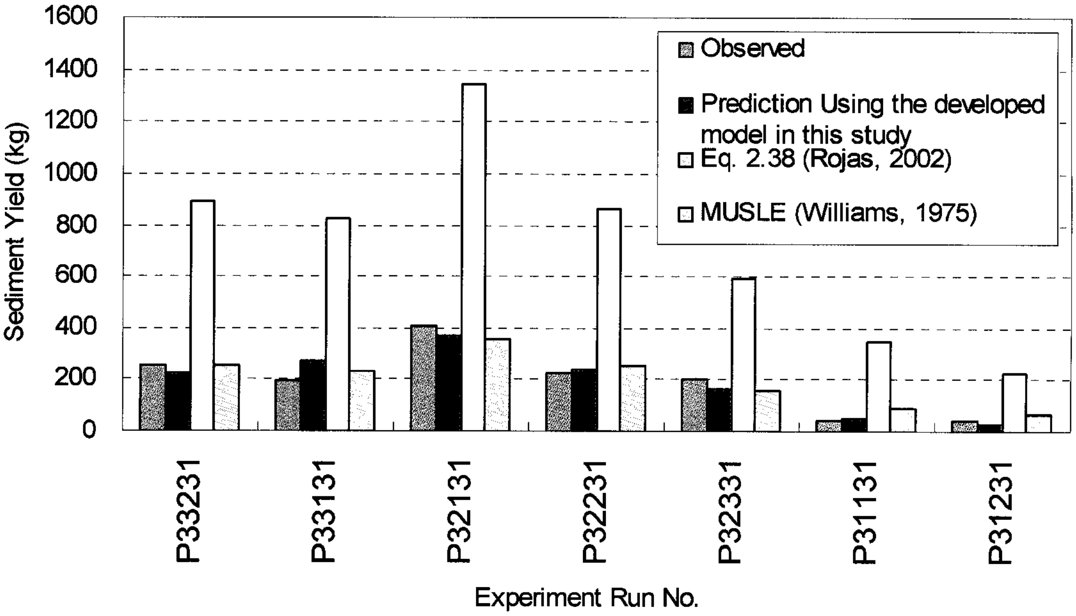


Figure 5.9. Sediment yield comparison between observed data and predicted values

Among the three equations used in Fig. 5.10, the equation developed in this study provided the best estimates of total soil yield, and the predicted values have a R^2 =0.95 to observed data. Over-estimations were shown by using Eq. (2.38).

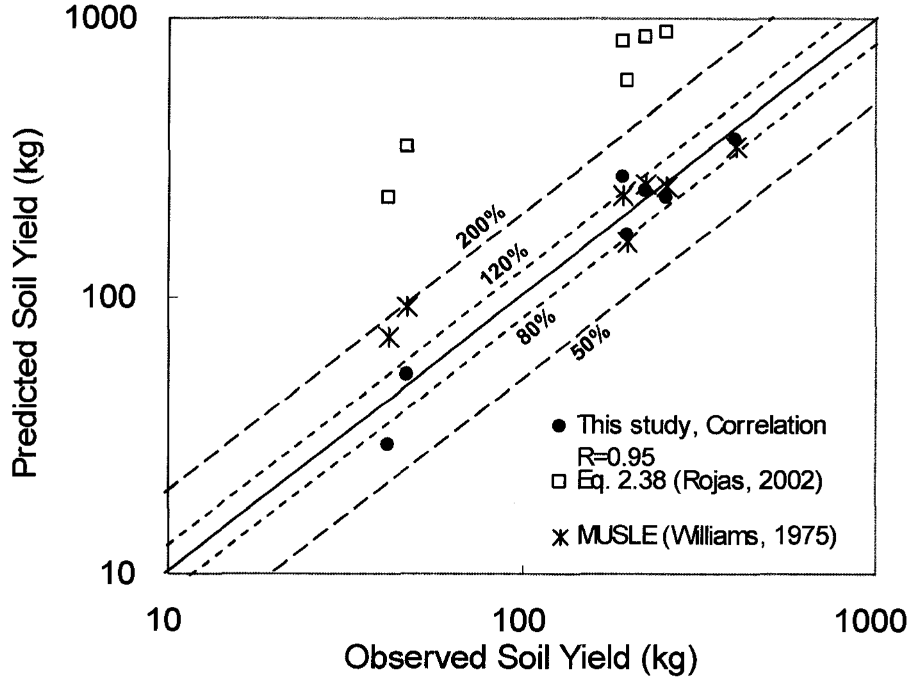


Figure 5.10. Sediment yield comparison between observed data and predicted values

5.5 Model validation

Many researchers use correlation and regression analyses to test the strength of association between predicted and observed values. However, a high and significant value of correlation coefficient does not necessarily imply that a model is performing well (Morgan 2005) because a regression model could include an error from inaccurately observed data. The efficiency coefficient (*CE*), proposed by Nash and Sutcliffe (1970), is often used as an alternative to the correlation coefficient to express the performance of a model:

$$CE = \frac{\sum (X_{obs} - X_{mean})^2 - \sum (X_{pred} - X_{obs})^2}{\sum (X_{obs} - X_{mean})^2} \tag{5.17}$$

where X_{obs} = the observed value, X_{mean}= the mean of a set of observed values and X_{pred} = the predicted value. Generally speaking, a CE value greater than 0.5 is considered satisfactory (Quinton 1997).

In this study, there are seven pairs of observed and predicted data, which are expressed in Fig. 5.10. Based on the definition of the CE value, Eq. (5.17), Table 5.7 summarizes the observed and predicted values using the developed equation developed in this study. The result of model validation calculation, Eq. (5.18), shows the CE has a value of 0.90 for the model developed in this study. The study model is considered satisfactory.

Table 5.7. Calculation table of the model validation

Run No,	Sediment Yield (kg)		$(X_{obs} - X_{mean})^2$	$(X_{pred} - X_{obs})^2$
	Observed	Predicted		
P33231	257	227	3739	879
P33131	193	268	4	5501
P32131	406	369	44481	1413
P32231	223	241	758	311
P32331	200	166	19	1139
P31131	47	52	21985	28
P31231	42	29	23587	161
Mean	195.43	Sum	94573	9432

$$CE = \frac{94573 - 9432}{94573} = 0.90 \tag{5.18}$$

To conclude the performances of using the overland flow soil transport model developed in this study, Eqs. (4.42) to (4.45) indicate that the model has good agreements with the sediment concentration data used in Fig. 4.7. In this section, by using an one-dimensional diffusive wave model of overland flow, Eqs. (5.10) to (5.16) have been tested satisfactorily with field plot data having a high *CE* value. These performances expressed a good applicability of the overland flow soil transport model developed in this study.

CHAPTER VI REVISED CASC2D-SED MODEL AND MODEL VALIDATION

6.1 Revised CASC2D-SED model

Based on the published program code of CASC2D-SED (Rojas, 2002), its channel flow and overland flow erosion routings are revised in this study. The revised CASC2D-SED program code is attached in Appendix G. The revised channel flow and overland erosion routings are described in the following sections.

6.1.1 Eight flow directions (D8) for channel routing

In many of the distributed hydrologic models, stream path and bed slope are important factors (Holmgren, 1994; Quinn et al., 1991; and Tarboton, 1997). In Rojas's (2002) CASC2D-SED model, channel flow routing is a one dimensional hydraulic model. Channel flow from the outgoing grid runs downstream into a neighbor grid. The flow directions are limited among the four directions on the main axes. It might cause an over estimation of channel length and increase the travel time of water and sediment transport in modeling hydrology events. This algorithm is called D4 in this study.

The most popular flow direction algorithm is the one that flow from an outgoing grid can follow downstream into one of its eight neighbor grids (four on the main axes, four on the diagonal). This algorithm is commonly named D8. Fig. 6.1 shows a D8 flow direction grid. There are eight directions with different values. This represents one numerical approximation of the flow direction field in the case of a square elevation grid representation of the elevation surface. A numerical representation of the flow direction field of each cell takes on one of eight values. Depending on which of its eight neighboring cells is in the direction of steepest descent, the flow in this grid will follow that direction. For example, Fig. 6.2 shows 3×3 grids and each grid has its own elevation value. Calculating the length between grids and the slope value can yield the steepest descent to give a flow direction for the center grid. The D8 algorithm can be applied well for distributed hydrology simulations and has been applied in many current GIS software systems.

In this study, the D8 algorithm is used to revise the channel flow routing in Rojas's (2002) CASC2D-SED model. Fig. 6.3 is a comparison between D4 and D8 algorithms. It shows that using D8 algorithms can more accurately describe channel pattern. The revised channel flow routing using D8 algorithm in this study can better represent the channel hydraulics in the distributed hydrologic model.

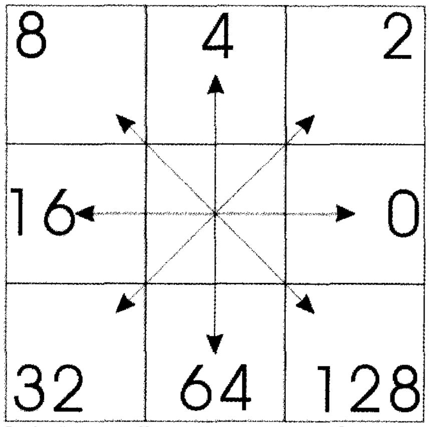


Figure 6.1. Flow direction grids of D8 algorithm

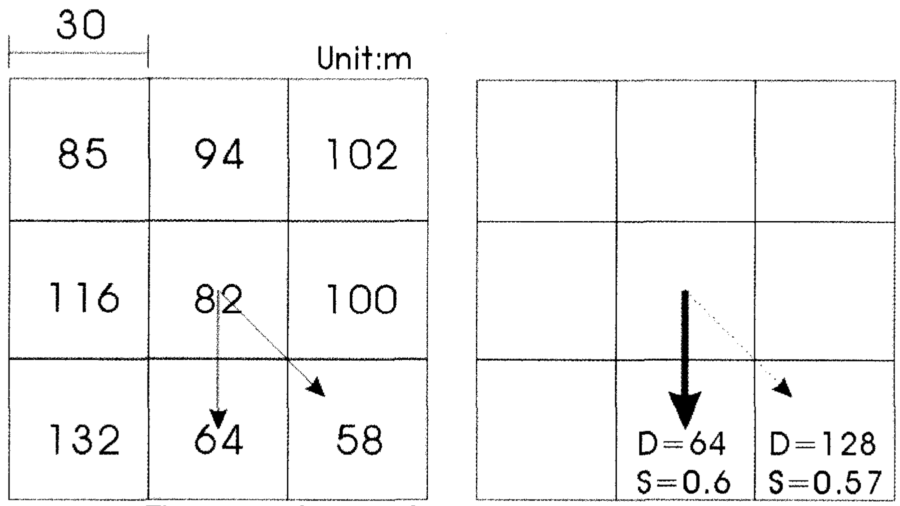
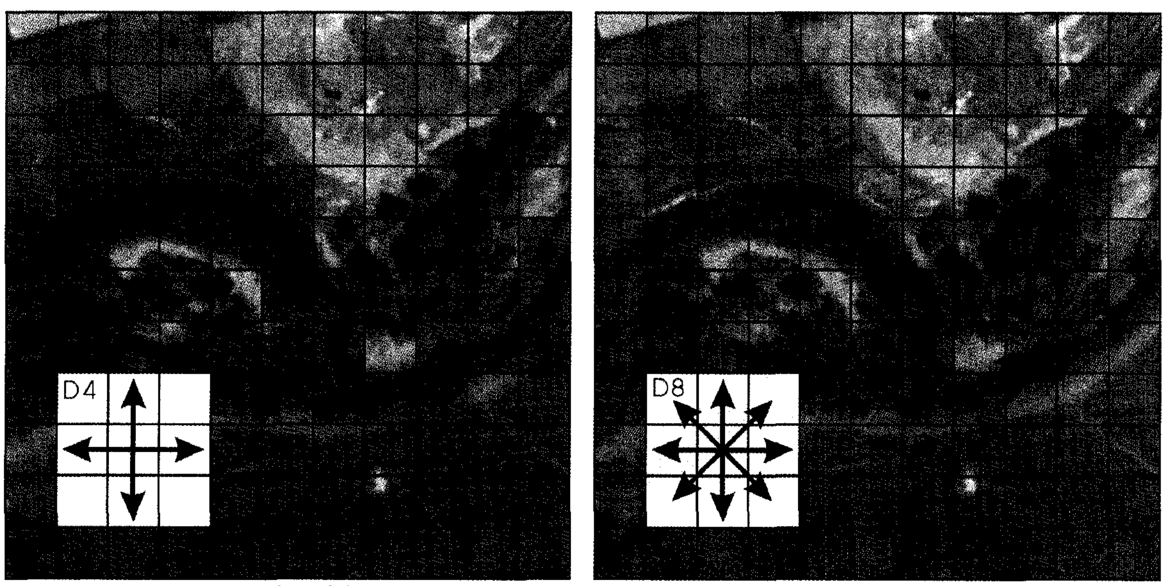


Figure 6.2. Select a flow direction grid using D8



a. D4 algorithm b. D8 algorithm

Figure 6.3. Channel patterns using D4 and D8 algorithms.

6.1.2 Revised overland flow sediment transport routing

CASC2D-SED uses a 2-D flow routing for overland flow. An overland roughness coefficient using Manning n_o is used in flow hydraulic routing. In the overland flow sediment transport routing, the modified Kilinc & Richardson (1973) transport capacity equation, Eq. (2.38), is used to estimate sediment transport capacity. It depends on overland flow characteristics, discharge, terrain slope, and soil and land use. It requires a crop management factor C as a resistance factor to reduce the efficiency of flow sediment transport capacity.

In this study, the overland flow sediment transport routing is replaced by the developed overland flow sediment transport model, Eqs. (5.10) to (5.16). The revised routing is based on flow unit stream power, soil erodibility, flow velocity, Froude number, flow discharge, and bed slope. For a storm event simulation, flow resistance effects are expressed in terms of flow velocity, Froude number, and unit stream power because these factors are important for the determination of overland flow sediment transport capacity. Based on important physical factors, the computed sediment transport capacity can reflect land cover change. The difference from Rojas's (2002) CASC2D-SED is that the revised overland flow sediment erosion routing can estimate soil erosion rates without using a C factor.

In the CASC2D-SED model, an outgoing grid receives suspended particles from upstream. By using the particle settling concept, coarser particles brought into suspension rapidly settle, while small fractions such as clay may remain in suspension due to their low settling velocity. The volume of suspended sediment that will settle depends on the total volume of the fraction in suspension, the particle settling velocity, and the water depth at the given grid. For detached particles, which are suspended or going to settle on the bed, their soil erodibility should be the maximum value, and flow has maximum efficiency to transport these detached particles. In this study, an erodibility K=1.0 is used to compute the overland flow soil transport capacity for these detached particles. When flow sediment transport capacity is greater than the volume of detached particles, these soil particles will be transported downstream to the receiving grid as suspended particles. The excess transport capacity is defined as the flow capacity producing erosion of the parent material when the transported volume of suspended and deposited sediment is subtracted from the total transport capacity. In this case, a soil erodibility, $K=K_b$, of the parent material is used to compute the eroded volume. K_b is the soil erodibility factor of parent material. Fig. 6.4 shows the soil erodibility values of detached soil particles and parent material in the revised CASC2D-SED. Fig. 6.5 is the new overland erosion and sediment transport processes schematics and flowchart revised from Rojas (2002).

In the revised overland flow routing, the developed overland flow transport equation is used to estimate sediment transport capacity based on important physical factors and to consider the limit of maximum concentration. In Rojas's (2002) CASC2D-SED, a unity K_b is used for both detached and parent materials and may cause more sediment transport capacity to be spent on transporting those detached particles. In this study, the revised overland flow sediment transport processes allow flow with greater sediment transport capacity than in Rojas's (2002) CASC2D-SED to transport detached particles, and more energy remains to erode parent material from the bed.

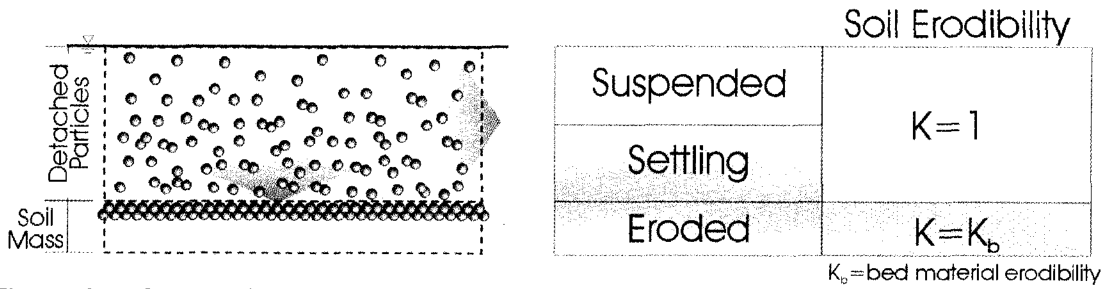


Figure 6.4. Soil erodibility factors used for detached soil particles and parent material in the revised overland flow erosion routing.

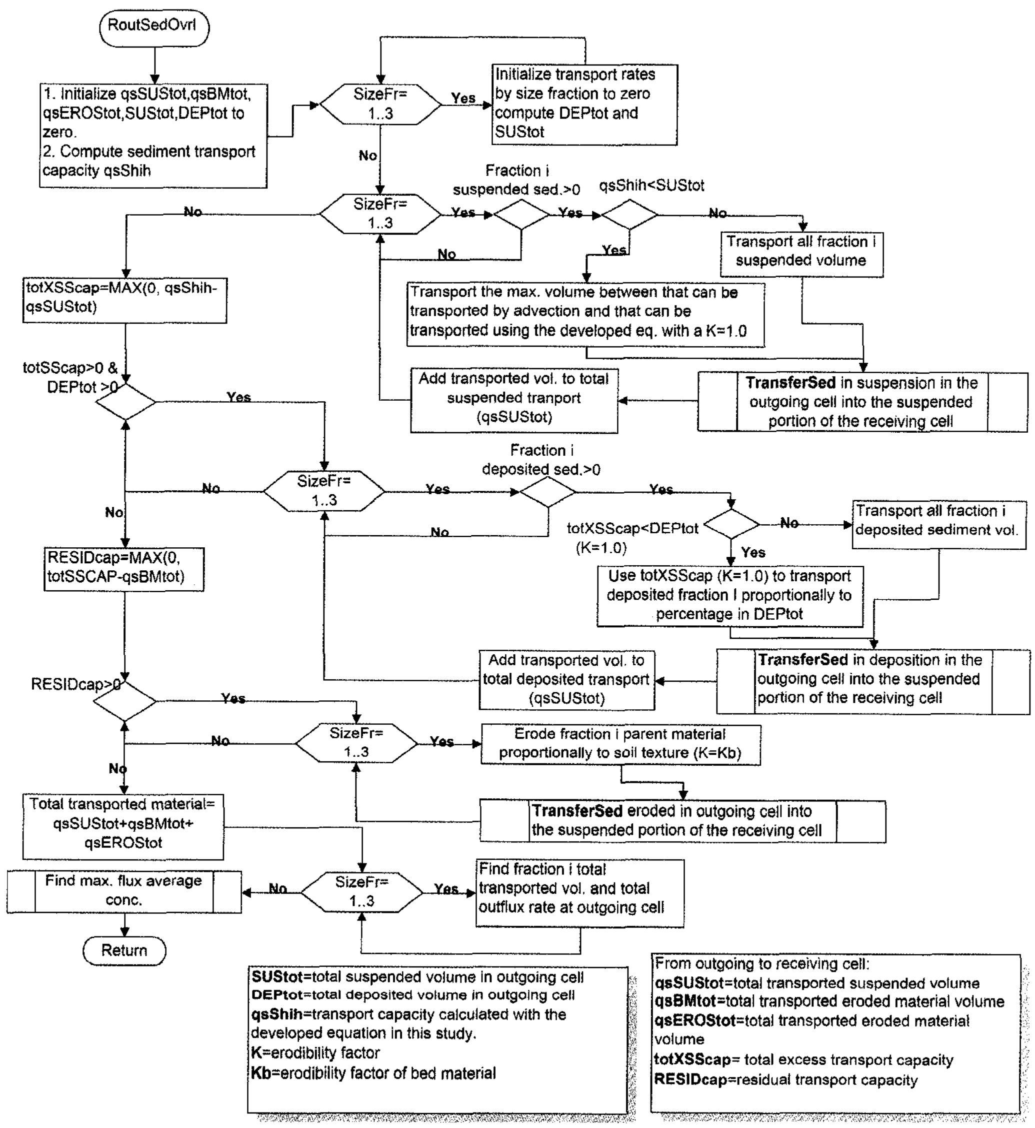


Figure 6.5. Overland erosion and sediment routing flowchart (Revised from Rojas 2002).

6.2 MODEL VALIDATION USING EXPERIMENTAL WATERSHED DATA

The Goodwin Creek experimental watershed in Mississippi and two experimental watersheds, Watersheds W2 and W3, of the U.S. Department of Agricultural Research Service in Iowa have detailed field data and gauge records. They have been selected to validate the revised CASC2D-SED in this study. The gauging station data, which includes rainfall, channel flow, and sediment yield at the outlets of the watersheds, were collected from these experimental watersheds. The watershed information, 2-D hydrology and sediment transport simulations, and comparisons between the observations and study results, are presented in the following sections.

6.2.1 Case I. Goodwin Creek experimental watershed, Mississippi

Goodwin Creek is a tributary of the Long Creek, which flows into the Yocona River, one of the main rivers of the Yazoo River Basin. The Goodwin Creek watershed is located in northern Mississippi, approximately 60 miles from Memphis, Tennessee and is extensively gaged by the Agricultural Research Service (ARS) as a research watershed for upland erosion, instream sediment transport, and watershed hydrology (Johnson, 1997). Fig. 6.6 shows the location of Goodwin Creek watershed.

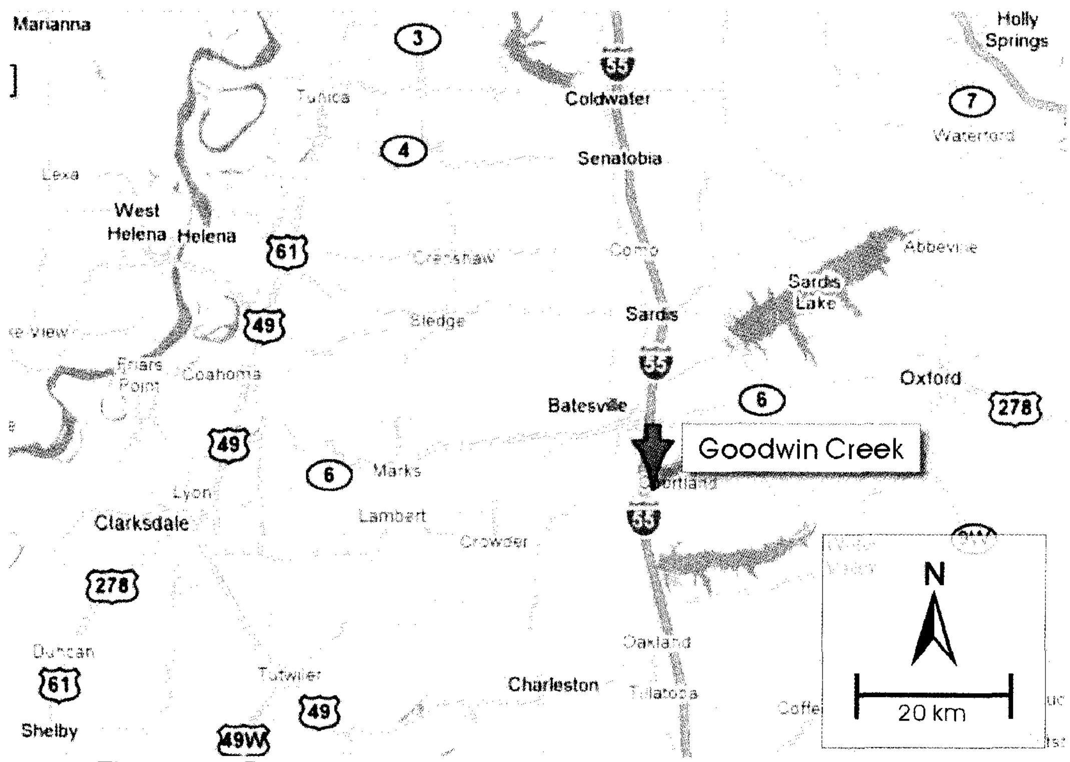


Figure 6.6. The location of Goodwin Creek watershed in Mississippi.

The Goodwin Creek watershed is divided into fourteen nested subcatctments with a flow measuring flume constructed at each of the drainage outlets (Fig. 6.7). Twenty-nine standard recording rain gages are uniformly located within and just outside the watershed. The climate of the watershed is humid, hot in the summer and moderate in the winter. The average annual rainfall was 56.7 inches from 1982 to 1992, and the mean annual runoff measured at the watershed outlet is 5.7 inches per year.

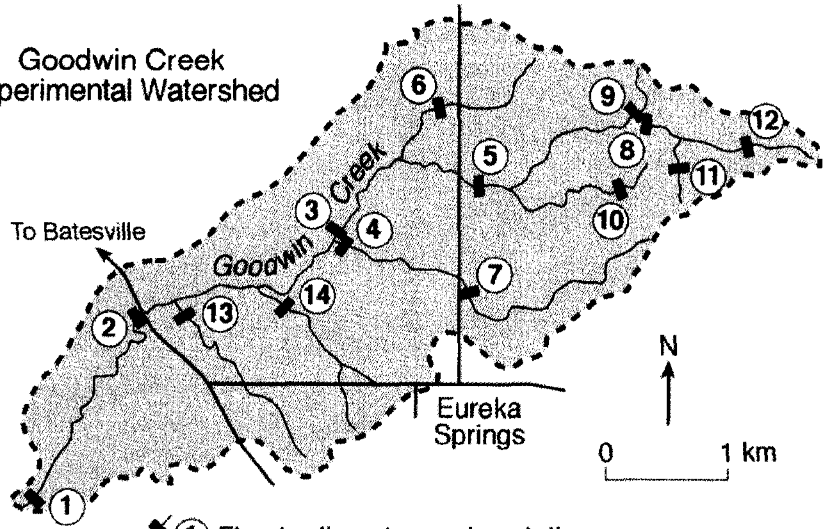


Figure 6.7. Locations of the gauge stations within the Goodwin Creek watershed in Mississippi.

In this study, the U.S. Geological Survey (USGS) 30m raster DEM data are used to delineate the watershed and river network. Fig. 6.8 presents the elevation, slope, flow direction, river network, sub-basins, land uses, and soil types of the watershed. The surface runoff flows approximately from northeast to southwest and drains a total area of 8.26 square miles. Terrain elevation ranges from 72 meters to 123 meters above mean sea level with an average channel slope of 0.004.

A storm event occurred on October 17th, 1981. This storm was simulated using CASC2D-SED in Rojas's (2002) study. It had a total rainfall duration of 4.8 hours with very little rainfall preceding it. Precipitation data were taken from sixteen rain gauges that are located within and just outside the watershed. The total rainfall depth for the event varied from 66 to 78.7 mm, with an average value of 73.6 mm. The average rainfall intensity was 14.7 mm/h, with a maximum of 51.6 mm/h (Rojas, 2002). Excluding the crop management factor *C*, the same inputs of rain gauge data, infiltration parameters, Manning roughness values of overland and channel grids, river network, soil erodibility, and distribution within the watershed are all applied to predict the hydrograph and sediment-graph curves by using the revised CASC2D-SED developed in this study. Table 6.1 shows the roughness values used for different land uses. Table 6.2 shows the soil friction and erodibility of each soil type. Within the Goodwin Creek watershed, a large part of watershed is covered by pasture and forest which are 58.8% and 26.7 %.

Table 6.1. Soil infiltration and erosion parameter values for the validation run (Rojas, 2002).

Soil Series	Erodibility Factor *K*	Hydr. Cond. K_s (cm/hr)	Suction Head (cm)	Moisture Deficit (%)	% Sand	% Silt	% Clay
Calloway	0.4	0.336	22	29	25	55	20
Fallaya	1	0.307	14	29	25	55	20
Grenada	0.2	0.355	17	29	30	60	10
Loring	0.4	0.365	22	29	25	55	20
Collins	0.2	0.346	18	29	30	60	10
Memphis	0.1	0.432	22	29	30	60	10
Gullied Land	0.1	0.384	15	29	25	55	20

Table 6.2. Land use parameter values for the validation run (Rojas, 2002).

Land Cover	Manning Roughness	Interception (mm)	USLE *P* Factor	% in area of the watershed
Forest	0.25	3	1	26.7
Water	0.01	0	1	0.4
Cultivated	0.10	1	1	14.0
Pasture	0.20	1.5	1	58.8

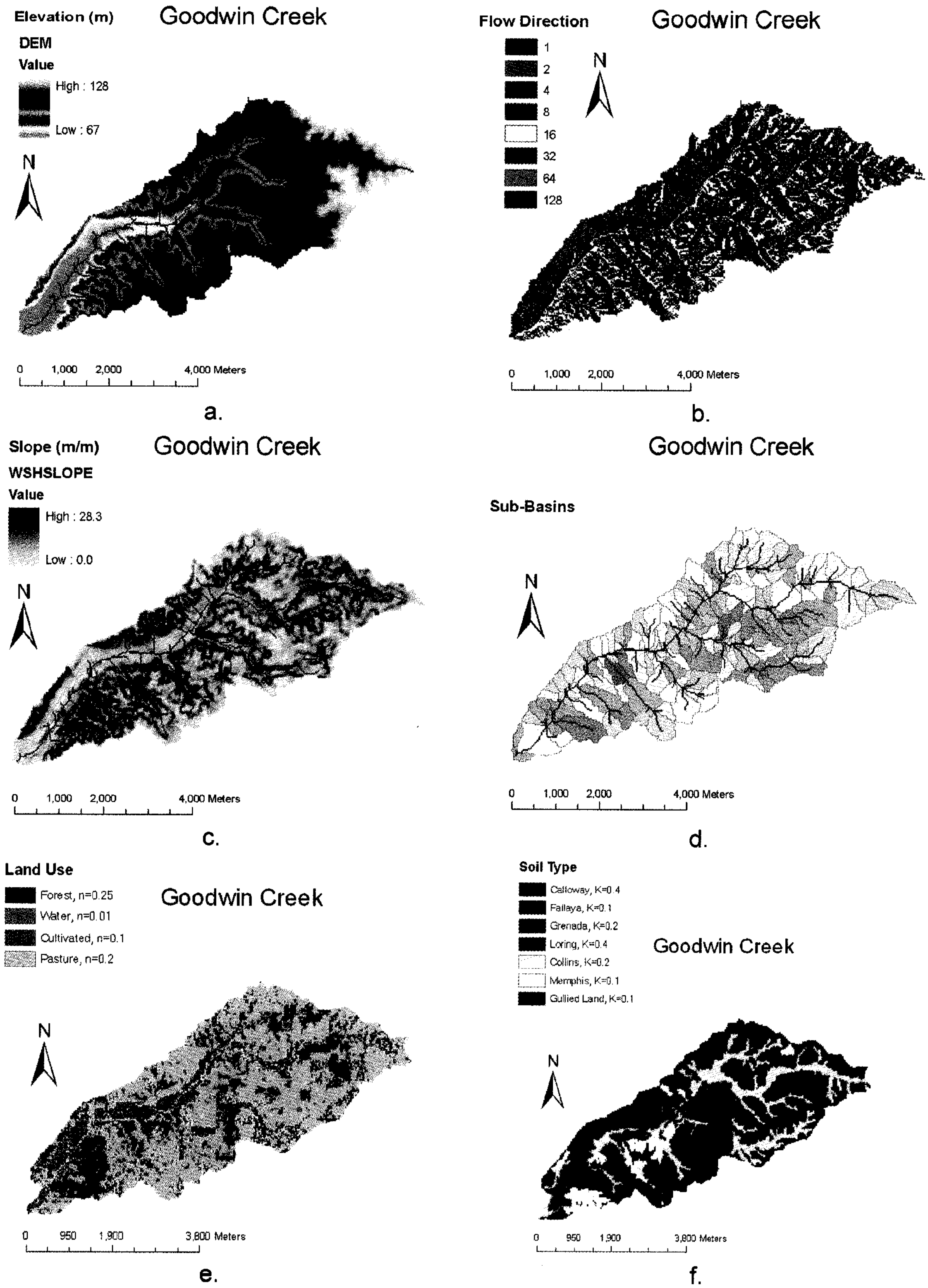
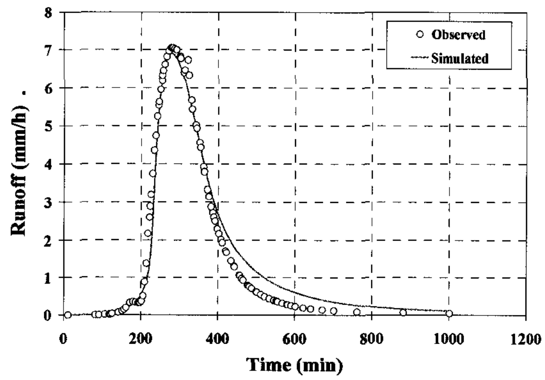


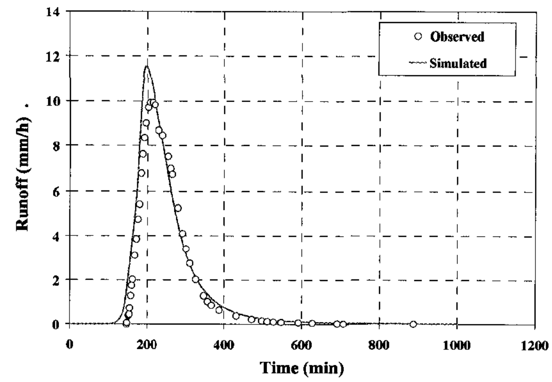
Figure 6.8. The DEM, soil and land use distributions of the Goodwin Creek watershed.

Six sub-basins, Numbers 1, 4, 6, 7, 8, and 14, are used to validate the revised CASC2D-SED, which uses the revised channel and overland flow routings in this study. The model inputs and outputs are given in the Appendix H.

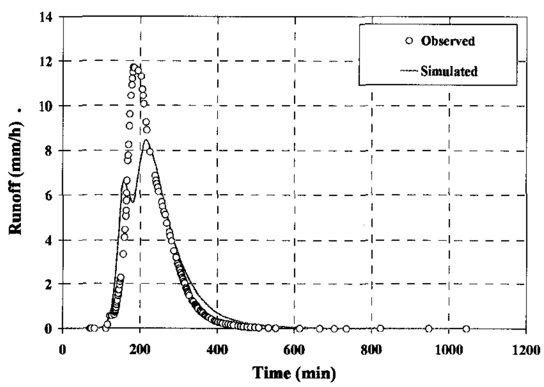
The predicted hydrographs and sediment-graphs of the selected sub-basins are compared to their observed data in Figs. 6.9 and 6.10. In addition, the predicted sediment-graphs which were done by (Rojas, 2002) are shown in Fig. 10 to compare with the simulations using the revised CASC2D-SED developed in this study. The predicted graphs are in good agreement with observed data in time series. At outlets No. 4 and No.7, Figs. 6.10.b and 6.10.d, the suddenly rising peaks of observed data may result from sudden bank failure or channel bed erosion. Channel bed and bank erosion cannot be computed by using CASC2D-SED. This may under-estimate soil yield in some watersheds which have incision channels. Using CASC2D-SED, the spatial distributions of rainfall intensity, infiltration, flow properties, and sediment transport can be exported into time series digital grids. Fig. 6.11 shows the total soil flux rate within the watershed. This can be used to indicate the hazard zone of soil loss within a watershed.



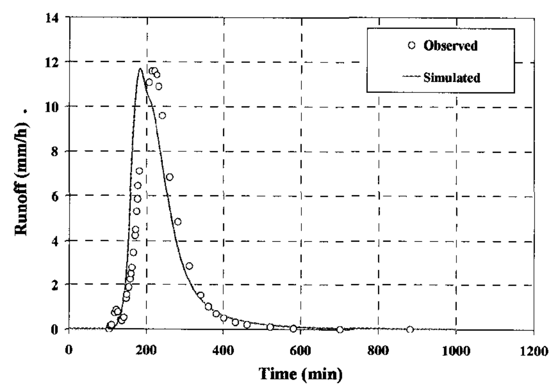
a. Gauge Station No. 1



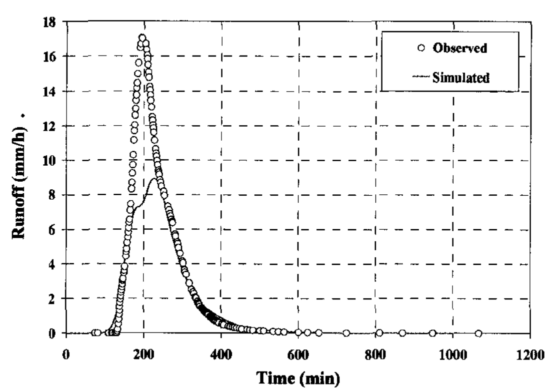
b. Gauge Station No. 4



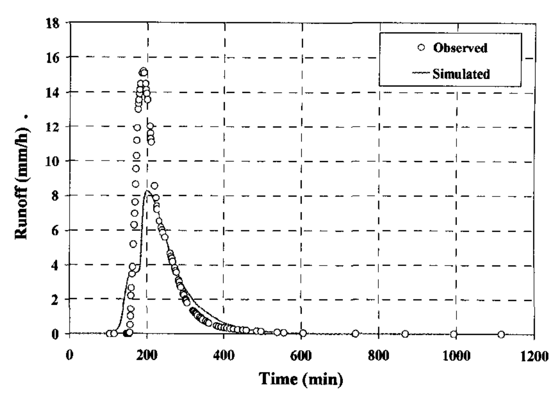
c. Gauge Station No. 6



d. Gauge Station No. 7



e. Gauge Station No. 8



f. Gauge Station No. 14

Figure 6.9. Computed hydrographs for the storm event on Oct. 17, 1981 using the revised CASC2D-SED.

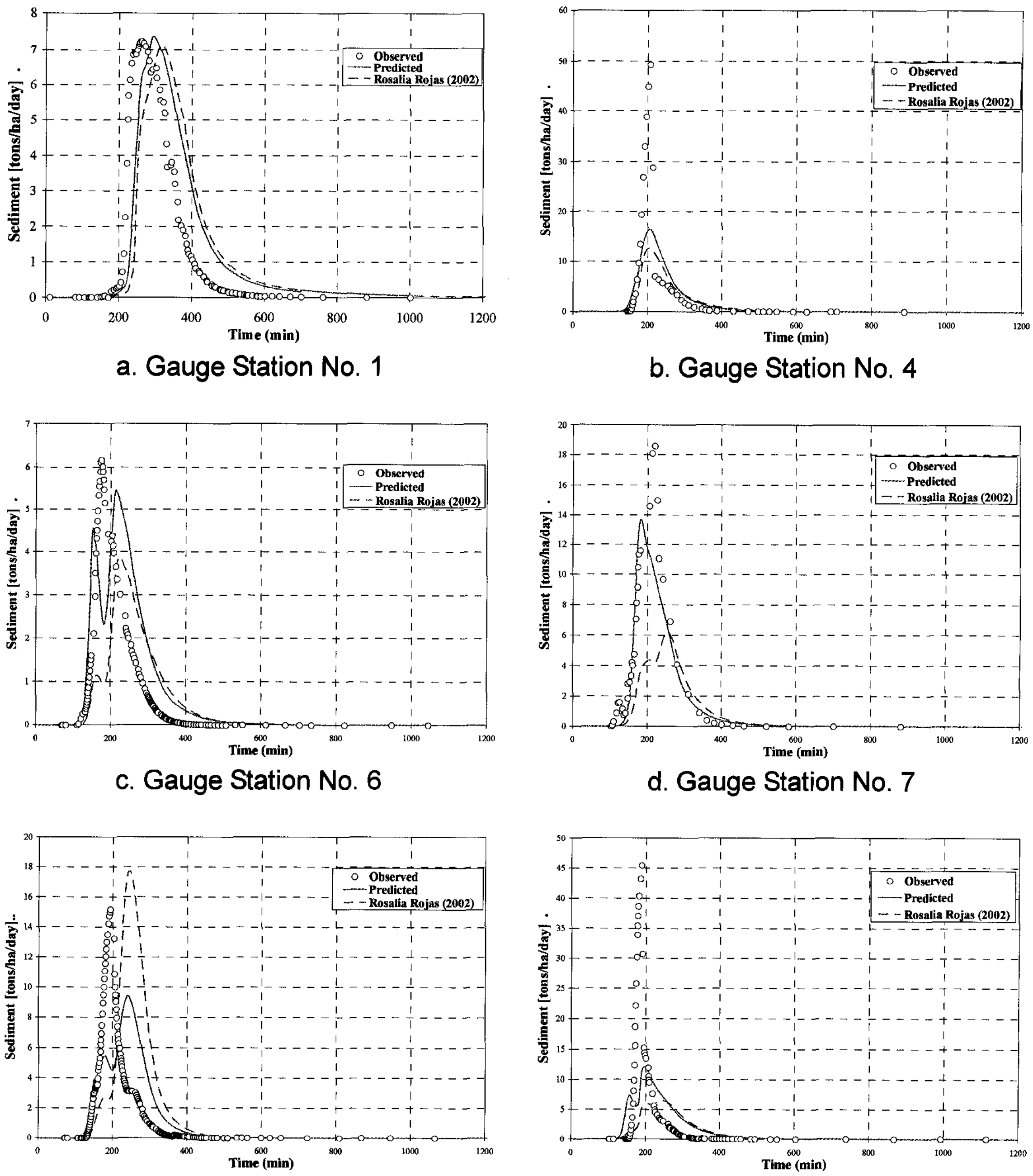


Figure 6.10. Computed sediment-graphs for the storm event on Oct. 17, 1981 using the revised CASC2D-SED.

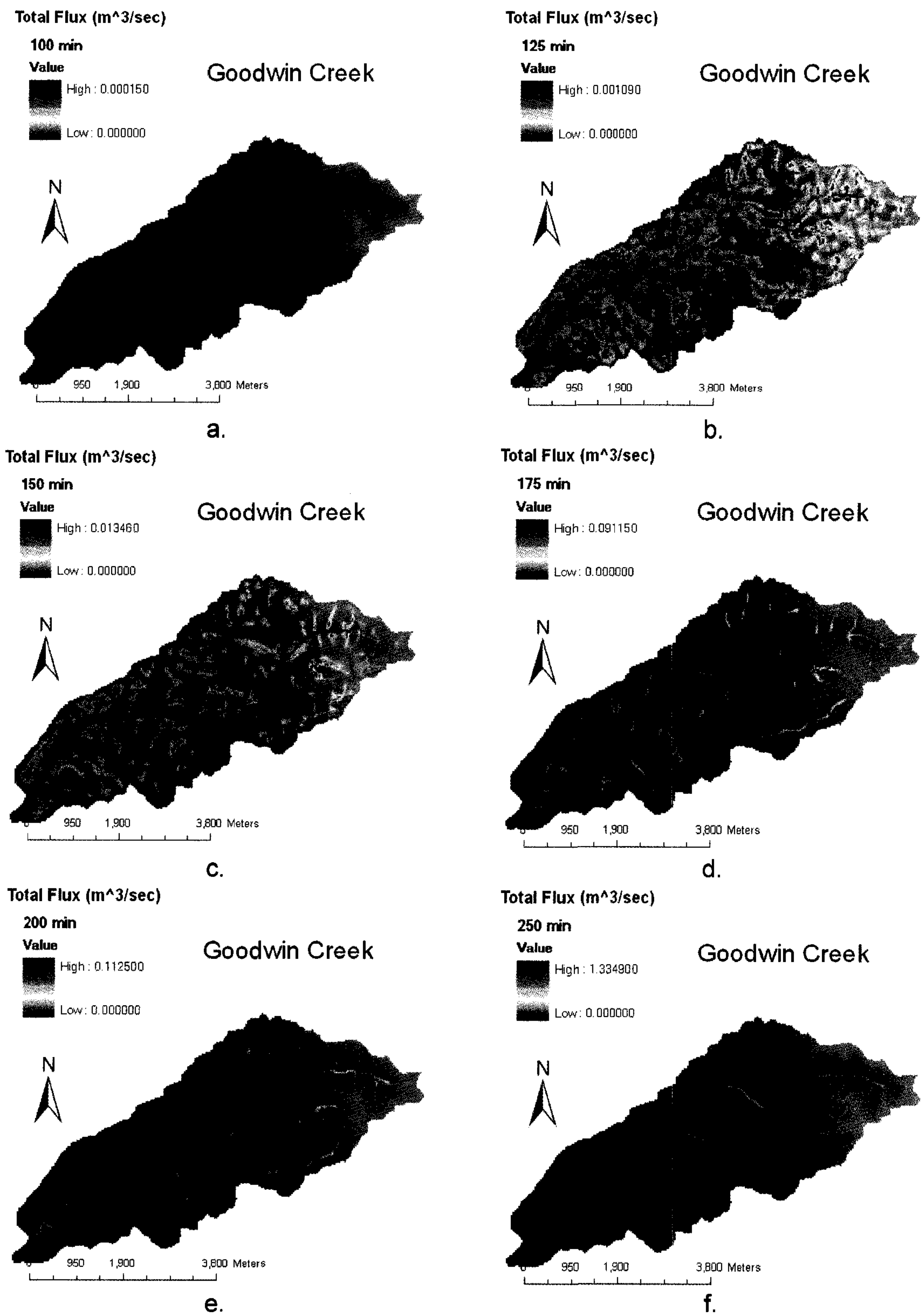


Figure 6.11. Time series grids of predicted total soil flux within the Goodwin Creek watershed.

To accumulate sediment yield from each simulation time interval, the total sediment yields in cubic meters from each sub-basin outlet are calculated. They are shown in Table 6.3 and Fig. 6.12 for the Oct. 17, 1981 storm event.

Table 6.3. Observed and predicted erosion volumes in study basins within the Goodwin Creek watershed.

Gauge No.		1	4	6	7	8	14
Basin Area (ha)		2052	356.5	120.5	162.5	155.5	162.6
Predicted Total Erosion Volume (Revised CASC2D-SED)	tons/ha	0.86	1.12	0.49	0.92	0.78	0.96
	m^3	667.61	150.54	22.25	56.35	45.94	58.67
Predicted Total Erosion Volume (CASC2D-SED)	tons/ha	0.86	0.91	0.34	0.57	1.11	0.66
	m^3	664.17	122.94	15.32	34.93	65.40	40.77
Observed Total Erosion Volume	tons/ha	0.66	1.23	0.33	1.02	0.63	0.92
	m^3	514.42	165.70	15.01	62.54	37.05	56.69

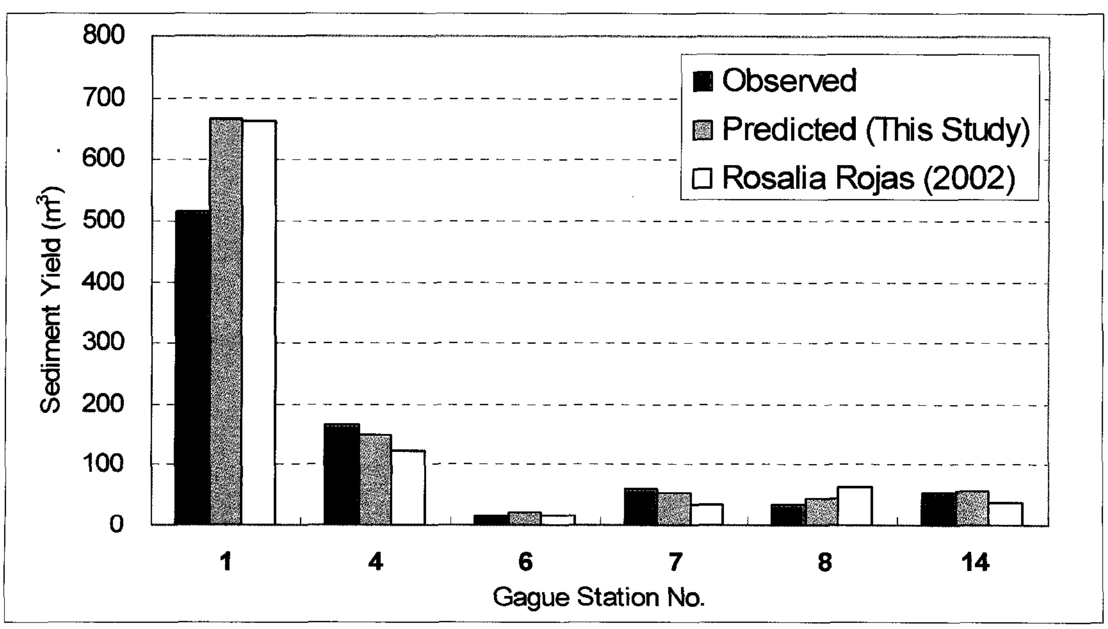


Figure 6.12. Predicted and observed soil yield from basin outlets within the Goodwin Creek watershed in Mississippi.

Fig. 6.13 shows a comparison of the CASC2D-SED (Rojas, 2002) and the revised CASC2D-SED developed in this study. It indicates that both models are accurate for observed data. Without using the USLE factor *C* required in CASC2D-SED, the revised CASC2D-SED developed in this study can reasonably predict soil erosion rate in the Goodwin Creek watershed.

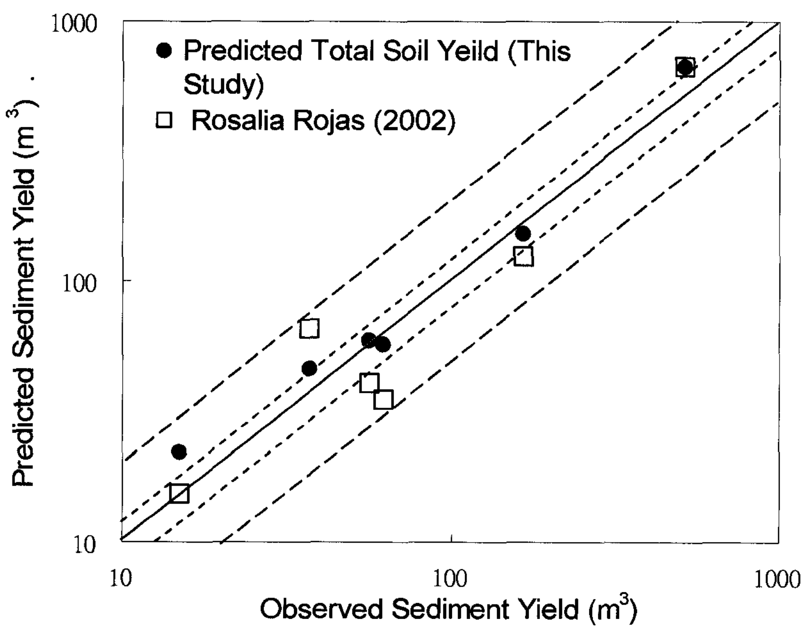


Figure 6.13. Comparison of observed and predicted total sediment yields at the outlets of the selected sub-basins for Oct. 17, 1981 storm event.

The validation index is applied to judge the satisfaction of using the revised CASC2D-SED. According to Eq. (6.1), there is a high efficiency coefficient *CE* of 0.87, which is greater than the satisfactory value of 0.5 to be valid. Fig. 6.14 shows the comparison of observed versus predicted excess flow volume and sediment yield from the selected sub-basins. These agreements with observed data support the use of the revised CASC2D-SED to predict water and sediment transport within the Goodwin Creek Watershed.

$$CE = \frac{\sum(X_{obs} - X_{mean})^2 - \sum(X_{pred} - X_{obs})^2}{\sum(X_{obs} - X_{mean})^2} = \frac{179993.85 - 23868.97}{179993.85} = 0.87 \qquad (6.1)$$

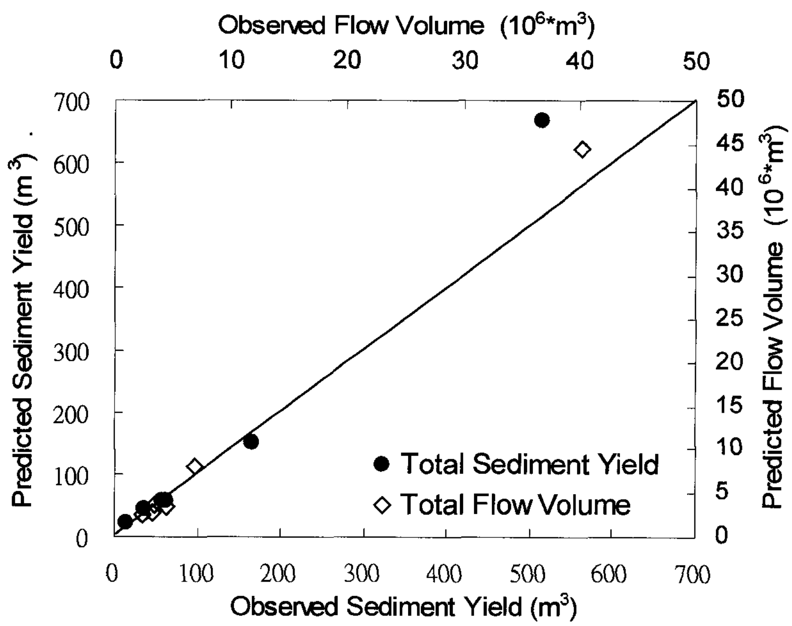


Figure 6.14. Observed vs. predicted total excess flow volume and sediment yield at the outlets of the selected sub-basins for Oct. 17, 1981 storm event.

6.2.2 Case II. Experimental Watersheds W2 and W3, Treynor, Iowa

Watersheds W2 and W3 are part of four experimental watersheds (W1, W2, W3 and W4) established by the U.S. Department of Agricultural Research Service (USDA-ARS) in 1964. They are small watersheds and are located near Treynor, Iowa, with areas of approximately 69 and 118 acres, respectively. Fig. 6.15 shows their locations.

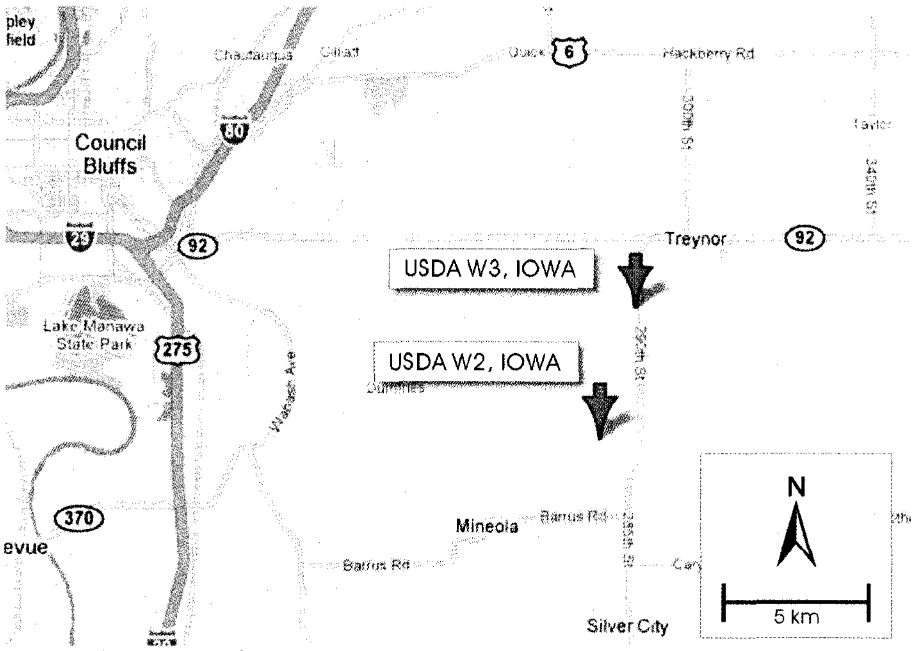


Figure 6.15. Locations of USDA-ARS W2 and W3 watersheds in Iowa.

Watersheds W2 and W3 are similar in characteristics, with rolling topography defined by gently sloping ridges, steep side slopes, and alluvial valleys with incised channels that normally end at an active gully head, typical of the deep loess soil (Kramer et al., 1990). Slopes usually change from 2% to 4% on the ridges and valleys, and 12% to 16% on the side slopes. An average slope of about 8.4% is estimated for both watersheds (Kalin, 2002). They are corn-cropped watersheds. Topsoil is mainly silt loam.

USDA-ARS National Tilt Laboratory, Iowa, provided runoff and sediment data covering a 30 year time span from 1964 to 1993 with more than 500 rainfall events. There are three rain gauges located around each watershed, rain gauges 115, 116 and 117 around W2 and 112, 113 and 114 around W3, respectively. A total of 14 rainfall events for W2 and 12 rainfall events for W3 were recorded by Kalin (2002). In this study, the gauge data of the storm event that occurred on June 13th, 1983 are used to validate the model simulations of runoff and sediment transport. Because the Watersheds W2 and W3 drain small areas, rainfall intensity is considered uniform in space. The rainfall data from rain gauges 115 and 112 are used to present the storm precipitation in Watersheds W2 and W3. Appendix F shows the flow and sediment discharge data from the outlets of watersheds W2 and W3, as well as rainfall intensity during the storm of June 13th, 1983.

The available DEM raster were obtained from the U.S. Geological Survey (USGS). Its resolution for Watersheds W2 and W3 is 10m by 10m, with a vertical resolution of 1ft (0.3048m). The USGS DEM data have been processed for Watersheds W2 and W3 in this study. The watersheds are delineated using GIS software. Fig. 6.16 represents the spatial distributions of elevation, slope and flow direction.

Kalin and Hantush (2003) simulated the storm hydrographs and sediment-graphs using the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model in the W2 watershed. GSSHA model is a reformulation and enhancement of the hydrologic model CASC2-D (Ogden and Julien, 2002). The sediment components are exactly the same as CASC2D-SED. In order to test the agreement between GSSHA inputs, which are used in the Kalin and Hantush (2003) study, and the revised CASC2D-SED, Tables 6.4 and 6.5 list the same input values of overland and soil properties within the W2 watershed from the Kalin and Hantush (2003) study. The suggested parameter values within the W3 watershed are referred from Kalin (2002) study and are shown in Tables 6.4 and 6.5.

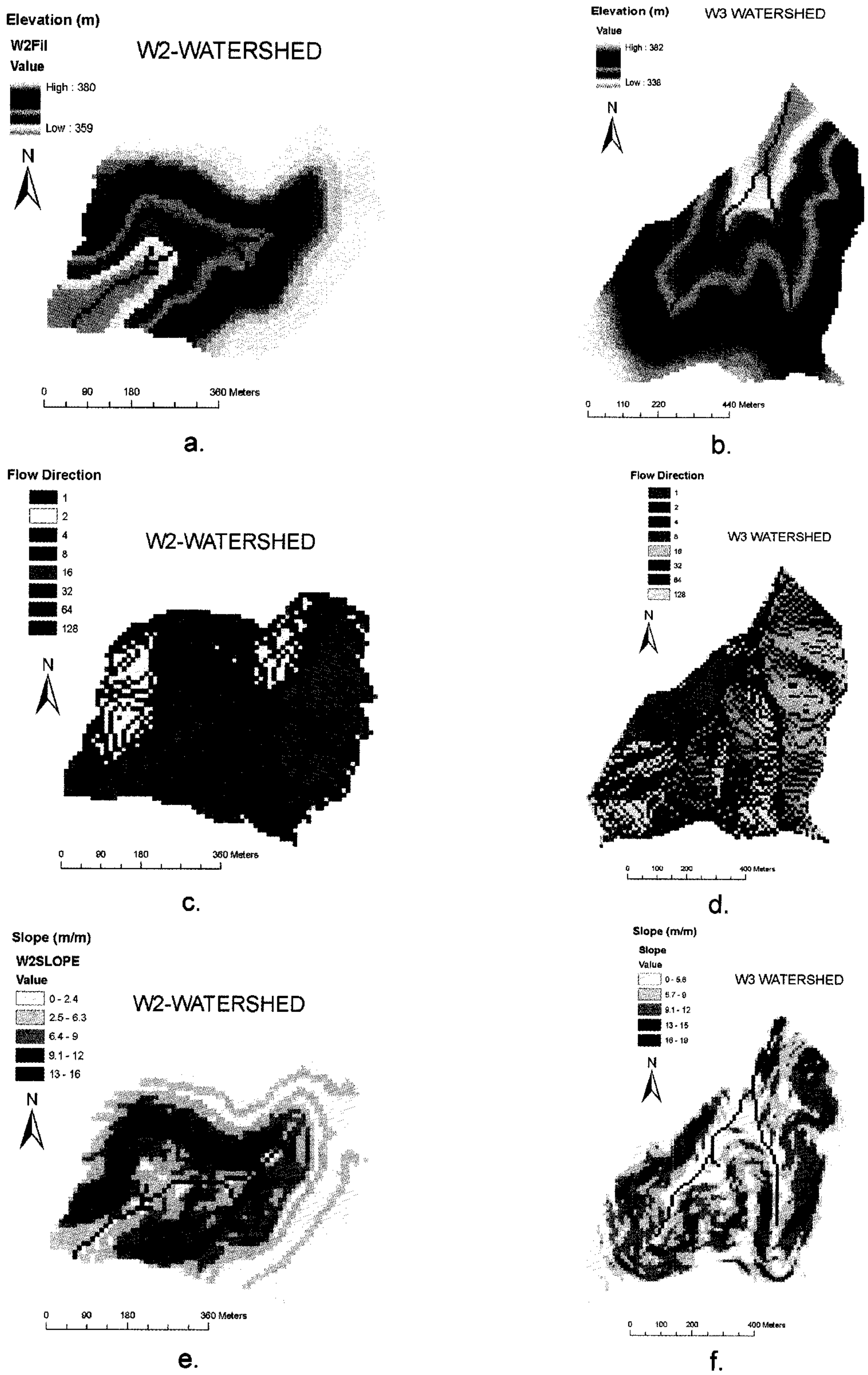


Figure 6.16. The digital elevation model of USDA-ARS Watersheds W2 and W3 in Iowa

Table 6.4. Soil parameter values for the validation runs in the Watersheds W2 and W3.

Basin	Erodibilty factor K	Hydr. Cond. Ks (cm/hr)	Suction Head (cm)	Moisture Deficit (%)	% Sand	% Silt	% Clay
*W2	*0.48	*0.35	*20	*27	*25	*61	*14
**W3	0.4	0.85	25	20	25	61	14

* Parameter values were calibrated and used in Kalin and Hantush (2003) study using GSSHA model.
**Parameter values were calibrated and used in Kalin (2002) study.

Table 6.5. Overland flow parameter values for the validation runs

Basin	Overland Manning Roughness	Interception (mm)
*W2	*0.04	*1.00
**W3	**0.20	**0.76

* Parameter values were used in Kalin and Hantush (2003) study using GSSHA model.
**Parameter values were calibrated and used in Kalin (2002) study.

Figs. 6.17, 6.18, 6.19, and 6.20 show the observed versus simulated flow hydrographs and sediment-graphs for Watersheds W2 and W3. They show good agreement between observed and predicted values using the revised CASC2D-SE. To compute total excess flow and sediment yield from watershed outlets, Fig. 6.21 shows that the predicted total volumes of excess flow and sediment yield are in good agreement with predicted values.

For Watershed W2, Figs. 6.17 and 6.18 show that there is good agreement between the GSSHA model used by Kalin and Hantush (2003) and the revised CASC2D-SED. Without using the crop management factor *C*, the revised CASC2D-SED using the soil erosion equation developed in this study still provides good simulations of sediment transport in Watersheds W2 and W3. Figs. 6.22 and 6.23 are the time series grids of total soil flux within watersheds. They describe the spatial distribution and soil source and transportation from upland area to the basin outlet. The input and output files of Watersheds W2 and W3 simulations are given in Appendix H.

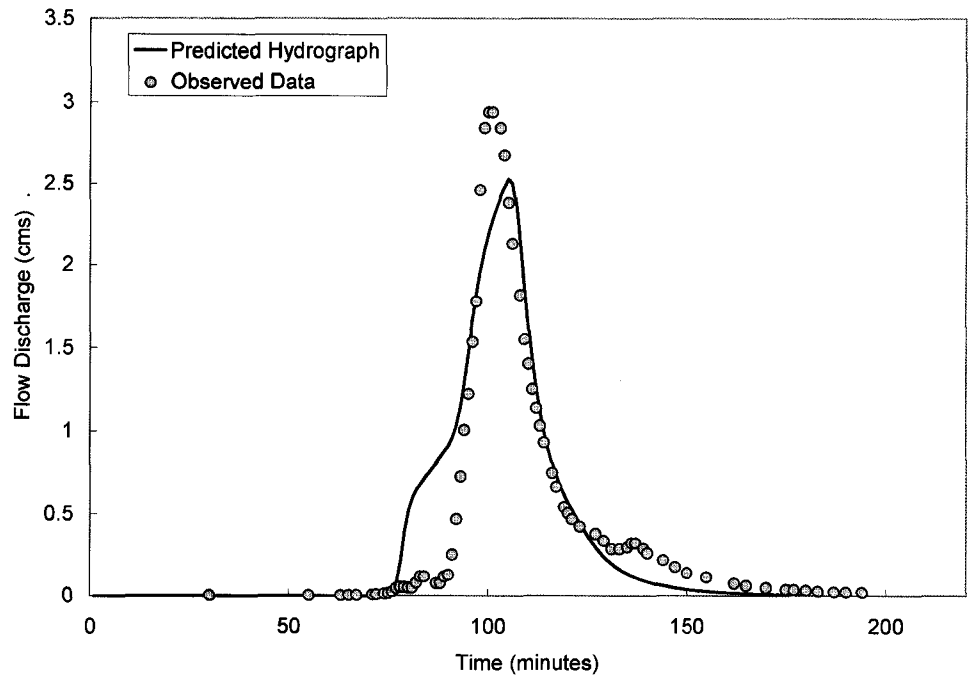


Figure 6.17. Comparison between the predicted and observed hydrographs in Watershed W2.

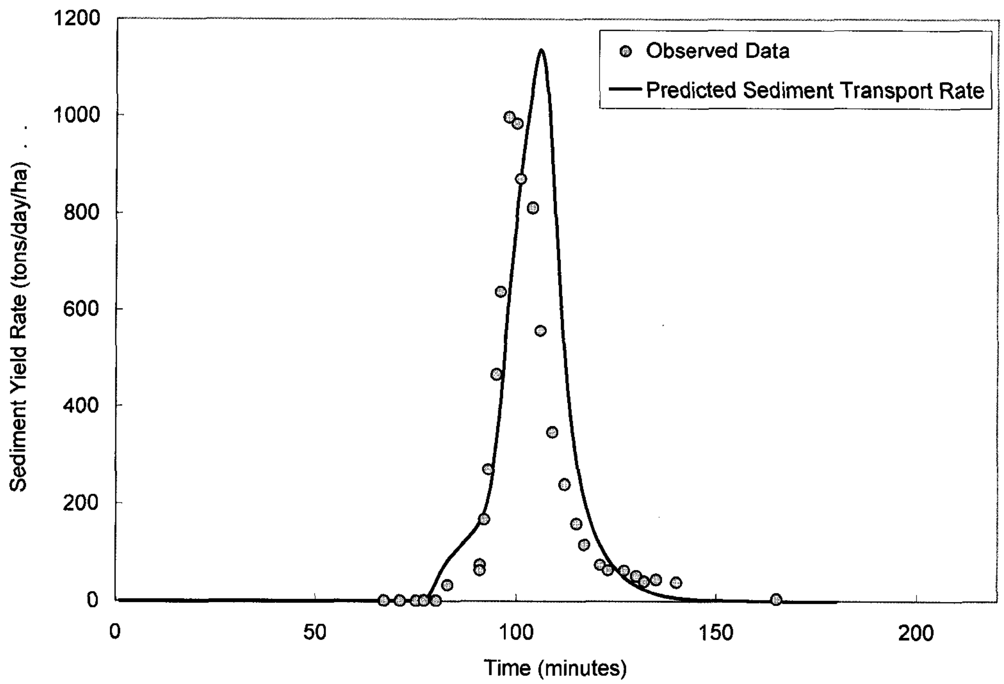


Figure 6.18. Comparison between the predicted and observed sediment graphs in Watershed W2.

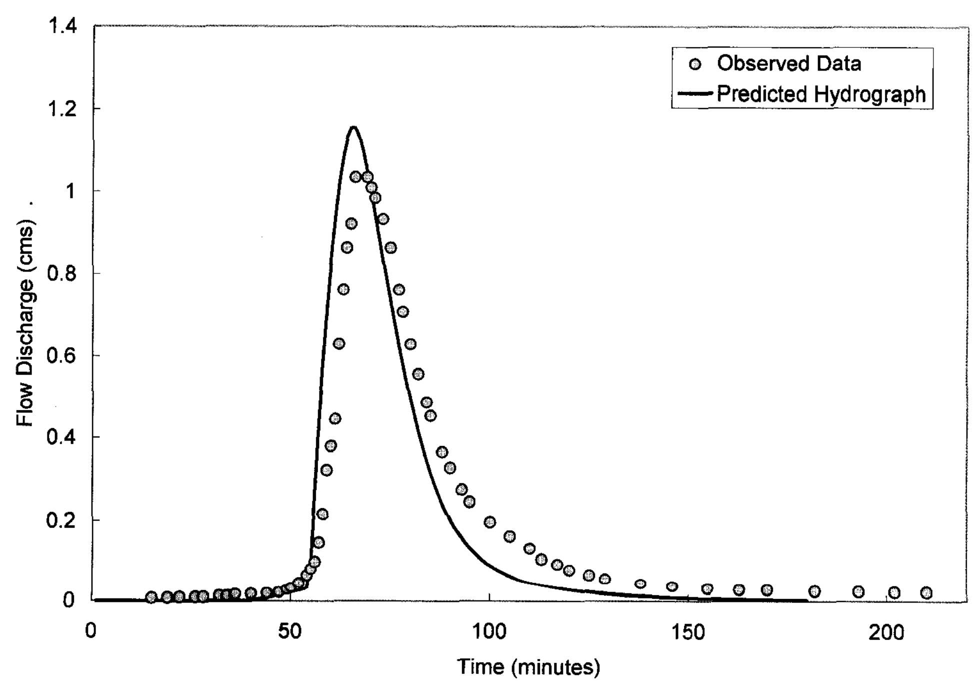


Figure 6.19. Comparison between the predicted and observed hydrographs in Watershed W3.

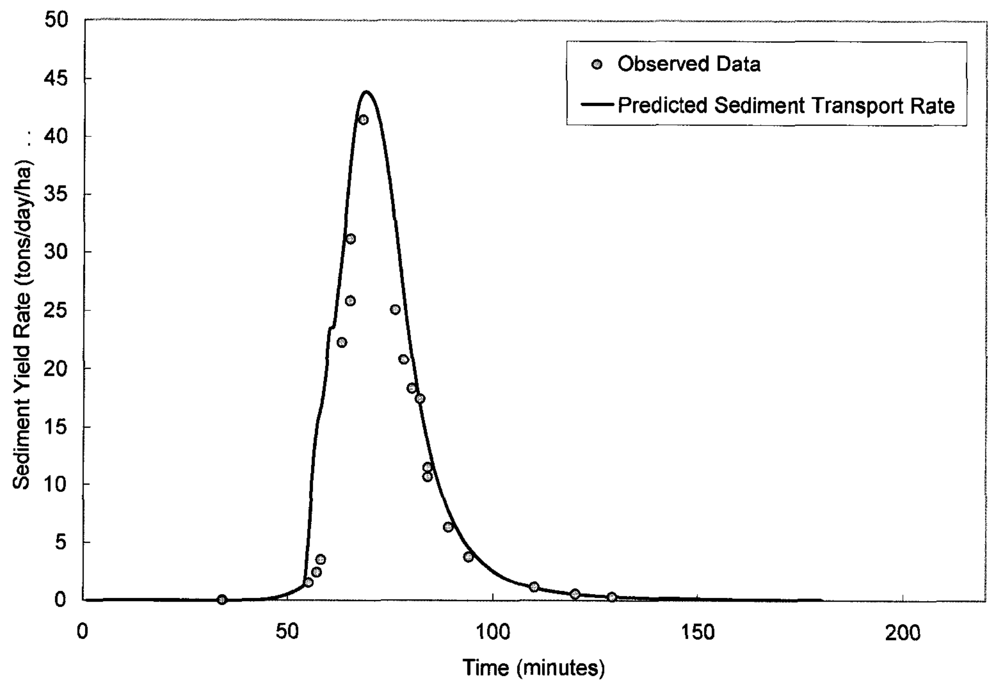


Figure 6.20. Comparison between the predicted and observed sediment graphs in Watershed W3.

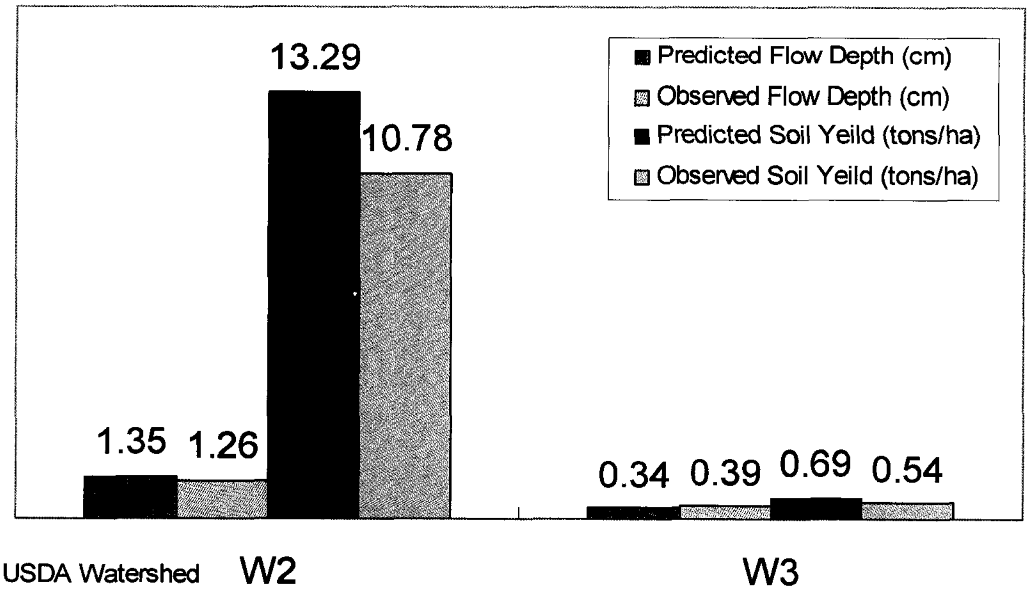


Figure 6.21. Comparison between the predicted and observed flow depths and sediment yields in Watersheds W2 and W3.

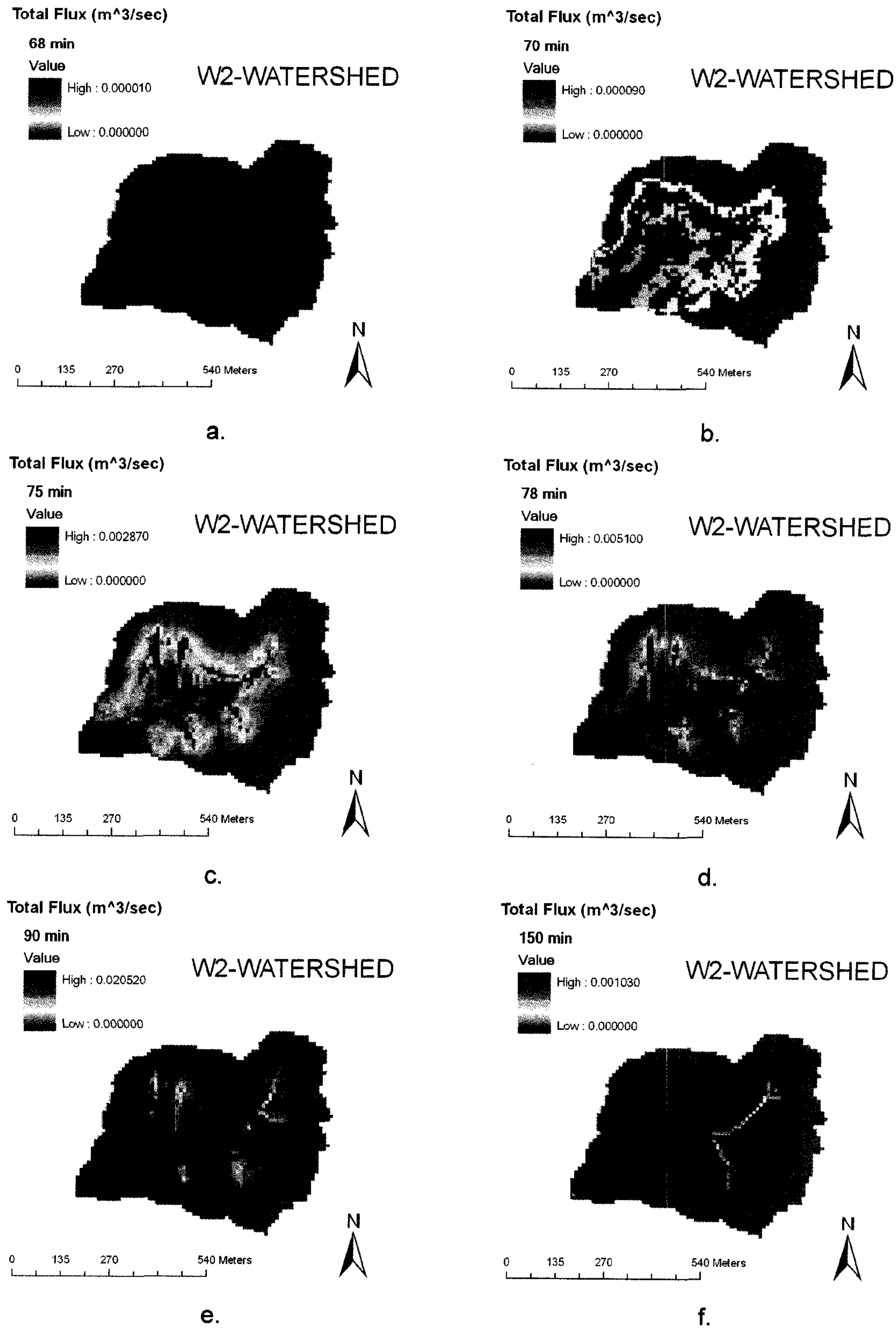


Figure 6.22. Time series grids of predicted total soil flux within the Watershed W2.

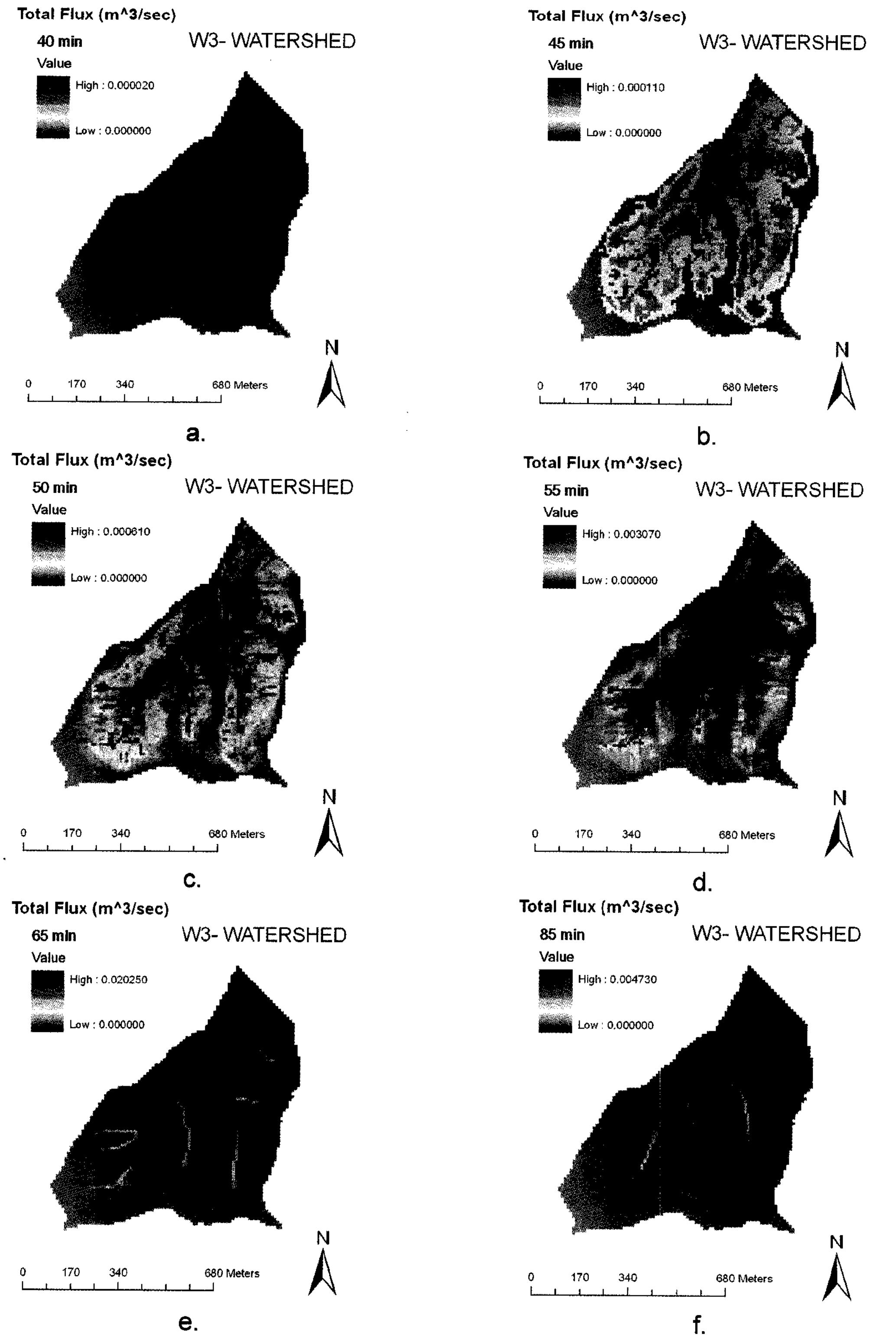


Figure 6.23. Time series grids of predicted total soil flux within the Watershed W3.

6.3 SENSITIVITY ANALYSIS OF RESISTANCE FACTORS

Using the current CASC2D-SED (Rojas, 2002), the Manning roughness coefficient n_o and crop management factor C depend on different land covers and are treated as resistance factors in the overland soil erosion calculations. The predicted soil erosion rates can vary with different factors. In this study, the overland flow resistance is considered as a significant factor for storm event based surface erosion because all soil particles have to be transported by running water. The developed soil erosion equation includes the consideration of flow velocity, slope, Froude number, and unit stream power. These factors can directly reflect the flow resistance impacts. The crop management factor C is not required in the input files for the application of the revised CASC2D-SED.

The resistance factors are empirically determined by using reference tables or field observation. However, there is a range of variation in resistance factor. There is a need to check the sensitivities of variation of these factors. The range from 50% to 200% of satisfactory resistance factors is used to compute the predicted flow discharge and soil yield at a basin outlet. For Rojas's CASC2D-SED, the resistance factors are overland Manning roughness coefficient n_o and crop management factor C. For the revised CASC2D-SED in this study, the resistance factor is the overland Manning roughness coefficient n_o only. USDA-ARS Watershed W2 with a storm event on June 13, 1981 is selected to perform the predicted results using various resistance factors.

According to the previous section, a Manning n_o of 0.04 is used in storm flow simulation for Watershed W2 on June 13, 1981. By changing overland Manning roughness coefficient n_o to 0.02, 0.028, 0.04, 0.052, and 0.08, the predicted total excess flow volumes at the basin outlet are shown in Table 6.6. The results show a range of 11% variation of using Manning n_o values from 50% to 200% of 0.04. The hydrographs are presented in Fig. 6.24. The times to peak flow are about the same. This shows that the effect on the hydrograph of changing Manning n_o is not significant for a small watershed.

Table 6.6. Sensitivity analysis of Manning n_o values for hydrograph computations.

Overland Manning Roughness Coeff.		Total Excess Flow Volume (m^3/m^2)	Difference	Range
Variation	Value			
200%	n_o=0.08	0.0126	-7%	11%
130%	n_o=0.052	0.0132	-2%	
0%	n_o=0.04	0.0135	0%	
70%	n_o=0.028	0.0138	3%	
50%	n_o=0.02	0.0141	4%	

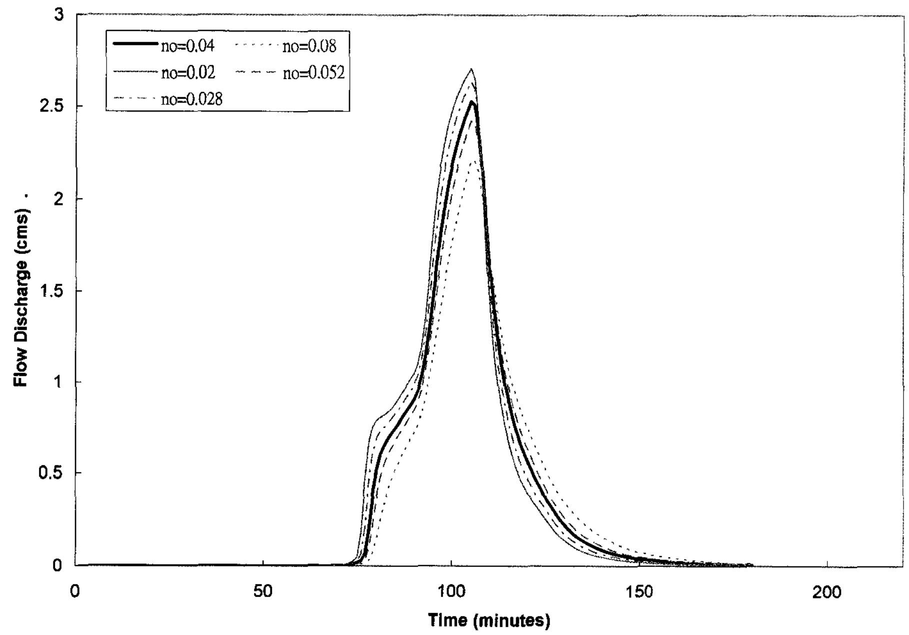


Figure 6.24. Computed hydrographs using Manning's n_o values of 0.02, 0.028, 0.04, 0.052, and 0.08.

6.3.1 Performances of soil yield simulation by varying Manning n_o using the revised CASC2D-SED

In the revised CASC2D-SED, efficiency of soil erosion is controlled by flow resistance, which varies with different overland Manning n_o values. By making overland Manning roughness n_o values equal to 0.02, 0.028, 0.04, 0.052, and 0.08, the predicted total sediment yields at the basin outlet are shown in Table 6.7. The maximum over estimation of 96% occurs when a 50% of n_o=0.04 is used in the simulation. An overall range between the maximum and minimum estimations is 148%. The overland roughness is more sensitive in sediment transport simulation than in hydrology simulation. Fig. 6.25 shows that the peak sediment transport rate decreases with increasing Manning roughness n_o.

Table 6.7. Sensitivity analysis of Manning n_o values for sediment yield computations

Overland Manning Roughness Coeff.		Event Sediment Yield		
Variation	Value	Tons/ha	Difference	Range
200%	n_o=0.08	6.40	-52%	148%
130%	n_o=0.052	9.97	-25%	
0%	n_o=0.04	13.29	0%	
70%	n_o=0.028	19.18	44%	
50%	n_o=0.02	26.03	96%	
		Max.	96%	
		Min.	-52%	

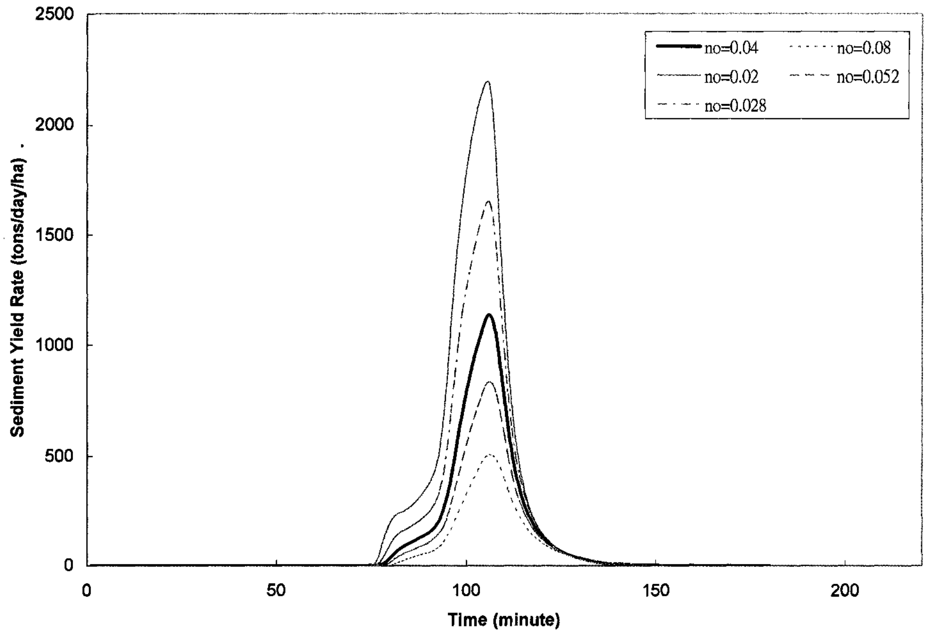


Figure 6.25. Computed sediment graphs using Manning n_o values of 0.02, 0.028, 0.04, 0.052, and 0.08.

6.3.2 Performances of soil yield simulation by varying Manning n_o and crop management factor C using Rojas's (2002) equation in CASC2D-SED

The resistance factors using Rojas's (2002) equation in CASC2D-SED are overland Manning roughness coefficient n_o and crop management factor C. A C = 0.1 is selected by calibration with observed data of Watershed W2 on June 13, 1981. The predicted volumes of excess flow and sediment yield using n_o = 0.04 and C = 0.1 are treated as observed data. The range from 50% to 200% of resistance factors is used to compute the predicted flow discharge and soil yield at a basin outlet. Manning roughness values of 0.02, 0.028, 0.04, 0.052, and 0.08, as well as crop management factor values of 0.05, 0.07, 0.1, 0.13 and 0.2 are used to simulate the storm. Based on all possible groups of Manning n_o and factor C, this study computes the predicted sediment-graphs and total sediment yield at basin outlet. Table 6.8 shows the simulated results and comparisons between different group sets. Predicted sediment-graphs are shown in Fig. 6.26.

Looking at each Manning roughness group in Table 6.8, a maximum range of 174% is performed at the group, n_o=0.02, with C values of 0.05, 0.07, 0.1, 0.13 and 0.2. The maximum estimated value of computed sediment yield is 135%, which occurs when n_o=0.02, and C=0.2. The minimum estimated value of computed sediment yield is -61%, which occurs when n_o=0.08 and C=0.05. An overall variation range between the maximum and minimum estimated sediment yields is 196%, which is greater than 148% of using the revised CASC2D-SED in this study.

A crop management factor C=0.042 was used for Watershed W2 by Kalin and Hantush (2003). The GSSHA model was used by them to compute the hydrology and sediment transport for the same event. However, the C factor of 0.1 needs to be used to satisfy the observed data. This shows that there may not be agreement for the use of C factor in different models.

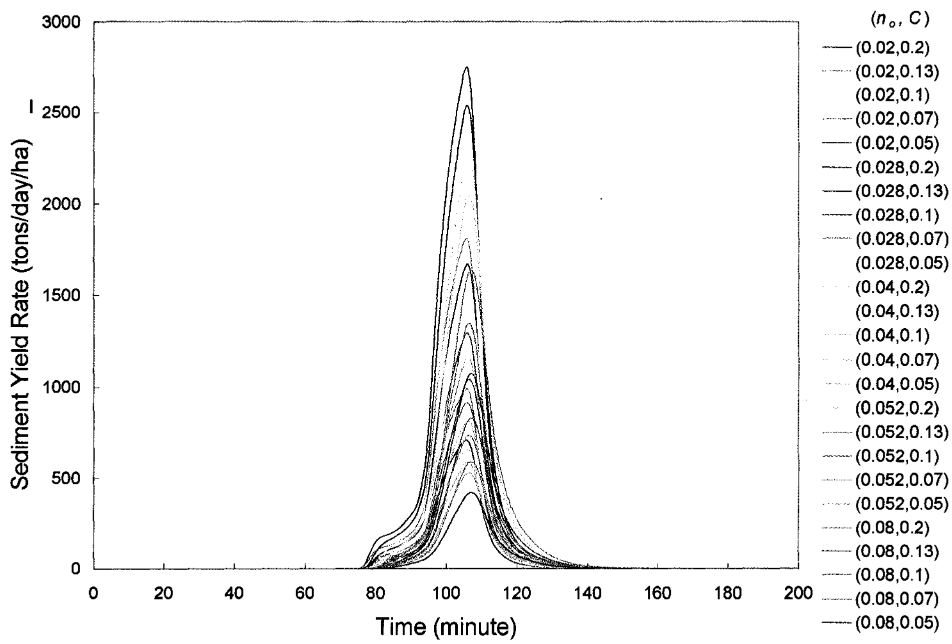


Figure 6.26. Sensitivity analysis of computing sediment graphs using different Manning n_o and factor C values.

Table 6.8. Sensitivity analysis of n_o and C values for sediment yield computations using Rojas's (2002) overland flow sediment transport equation.

Manning n_o		Land Cover Management Factor C		Total Sediment Yield		
Difference	Value	Difference	Value	(tons/ha)	Difference	Range
50%	0.02	200%	0.2	28.7	135%	174%
		130%	0.13	18.9	55%	
		-	0.1	14.67	20%	
		70%	0.07	10.39	-15%	
		50%	0.05	7.49	-39%	
70%	0.028	200%	0.2	26.46	117%	160%
		130%	0.13	17.42	43%	
		-	0.1	13.52	11%	
		70%	0.07	9.58	-21%	
		50%	0.05	6.91	-43%	
-	0.04	200%	0.2	23.86	96%	145%
		130%	0.13	15.7	29%	
		-	0.1	12.19	0%	
		70%	0.07	8.64	-29%	
		50%	0.05	6.23	-49%	
130%	0.052	200%	0.2	21.8	79%	132%
		130%	0.13	14.34	18%	
		-	0.1	11.14	-9%	
		70%	0.07	7.89	-35%	
		50%	0.05	5.69	-53%	
200%	0.08	200%	0.2	18.22	49%	100%
		130%	0.13	11.99	-2%	
		-	0.1	9.31	-24%	
		70%	0.07	6.59	-46%	
		50%	0.05	4.77	-61%	
			Overall	Max.	135%	196%
				Min.	-61%	

6.4 Discussion

The storm event simulations using the revised CASC2D-SED are in good agreement with observed hydrology and sediment transport data in the Goodwin Creek watershed, and Watersheds W2 and W3. The revised model was independently validated using additional data. The inputs of land cover and soil properties used in model validation are in agreement with the Rojas (2002) and Kalin and Hantush (2003) studies. Using the revised CASC2D-SED, the crop management factor C is not a required input. Because the important physical variables of flow velocity, bed slope, Froude number, and unit stream power used in the developed overland flow soil erosion model can reflect the flow resistance effects, the revised model can change computed sediment yields based on different flow resistance conditions.

A range of 50% to 200% is generally considered by sedimentation engineers to be acceptable when comparing computed sediment yields versus actual sediment yields (Johnson et al., 2000). By using a variation range of 50% to 200% of resistance factor values, the revised CASC2D-SED has a maximum difference range of 148%, which is less than the 196% from using Rojas's (2002) equation in CASC2D-SED. Although the predicted sediment yield is sensitive to the change of Manning roughness, the revised CASC2D-SED can still be considered a good model to compute the event based sediment transport within a watershed without considering the variation of Manning roghness coefficient n_o. The suggested DEM resolution for the revised CASC2D-SED is from 10m to 30m because these grid sizes are validated in the study.

CHAPTER VII CONCLUSIONS

7.1 Conclusions

This study shows that a method based on the unit stream power can be applied to the estimation of overland flow sediment transport rates with accuracy. Conclusions regarding the physically based regression analysis, 1-D and 2-D overland flow erosion modeling, and the revised CASC2D-SED model are summarized below.

Correlation and regression analyses showed that unit stream power has the highest correlation, $R = 0.94$, among velocity, slope, shear stress, unit discharge, stream power, and dimensionless unit stream power for the determination of surface erosion rate. Flow velocity, slope, and Froude number are other important factors for overland flow sediment transport.

A revised Weibull Function based regression formula is used to develop the overland flow sediment transport equations. The equation thus developed can predict sediment transport rate with varying flow conditions and rainfall impact. It covers a wide range of ε and β, exponents of the unit discharge q and bed slope S used in the equation. The equation also includes the consideration of maximum and minimum sediment concentration limits. The computed results agree with observed data very well. Sensitivity analysis results show that unit stream power is the most important parameter for the estimation of surface erosion rate. This is consistent with the use of unit stream power in a sediment transport equation for rivers.

The soil erosion equation developed in this study can be applied to field conditions using a dimensionless soil erodibility factor *K'*. A 1-D diffusive overland flow routing model was developed using the MacCormack scheme. Seven experimental runs of field data (Barfield et al, 1983) agree with simulated results using the soil erosion equation developed in this study and the 1-D diffusive wave model. A high efficiency coefficient of CE=0.90 for model validation in this study confirms that the model is satisfactory with field plot size.

The channel and overland flow routings of Rojas's (2002) CASC2D-SED program are revised in this study. A D8 algorithm is used to describe the channel flow direction. The developed overland flow erosion equation is used to compute overland flow soil erosion rate, and the soil erodibility factor is used only when flow detaches the parent material from the ground. For detached particles, the soil erodibility factor is unity. The revision increases computation accuracy of channel geometry characteristics and estimates the overland flow sediment transport rate based on using the unit stream power. The revised CASC2D-SED was validated using eight catchments in three experimental watersheds, and the predicted results are in good agreement with observed data. The variation of predicted results is within the acceptable range when the Manning roughness coefficient varies between 50% and 200%.

The unit stream power method has been shown to be a powerful tool for the analysis of sediment transport. Data from laboratory experiments, field plots, and experimental watersheds used in this study have shown that the surface erosion equations based on unit stream power as their dominant variable have very high reliability for the determination of erosion rate of overland flow. By revising Rojas's (2002) CASC2D-SED program, this study provides a management tool to predict or identify the distribution and potential of overland flow erosion in a watershed using the unit stream power.

7.2 Suggestions for Future Study

The limit of maximum concentration is included in the soil transport capacity equation developed in this study. This could avoid over-estimation using traditional soil erosion equations. However, the sediment data used to develop the equation in this study are much less than the maximum concentration. The equation probably has a weak statistically relationship at high sediment concentration. It will improve the prediction accuracy to have high concentration data used in the equation development.

The soil transport equation developed in this study may not be practically applied in the field because flow velocity and flow depth is not easy to be measured. This shows a need of improving field measurement technique. For a numerical modeling, the Manning equation and Manning roughness coefficients are used to compute flow velocity and depth. However, it is a complex problem to estimate roughness coefficient values. In order to increasing simulation accuracy, the values of roughness coefficients need to be calibrated using gauge data or provided by a more physical and accurate estimation.

Using CASC2D-SED only estimates the soil erosion from upland area. However, within some basins with incising channels, a large portion of watershed sediment yield may result from erosion occurring at channel bank and bed. To improve the estimations of flow resistance and to couple with channel soil erosion computation would be the future tasks of watershed soil erosion research.

REFERENCES

Aldridge, B.N., and Garrett, J.M., 1973, Roughness coefficients for stream channels in Arizona:U.S. Geological Survey Open-File Report, 87 p.

Aksoy, Hafzullah and Kavvas, M. Levent, 2005. A review of hillslope and watershed scale erosion and sediment transport models. Catena, 64, P. 247-271.

Aziz, N. M. and Scott, D. E. 1989. Experiments on sediment transport in shallow flows in high gradient channels. J. Hydrol. Sci., 34, 465-478.

Bagnold R. A. 1956. The flow of cohesionless grains in fluids. Phil. Trans. R.Soc. London, Series A, 964, 235-297.

Barekyan, A.S. 1962. Discharge of channel forming sediments and elements of sand waves. Soviet Hydrol. Selected Papers (Transactions of AGU No. 2), 128-130.

Barfield, B. J., R. I. Barnhisel, J. L. Powell, M. C. Hirschi and I. D. Moore, 1983, Erodibilities and Eroded Size Distribution of Western Kentucky Mine Spoil and Reconstructed Topsoil, Final Report for Title III Grant No. G1115211, Institute for Mining and Minerals Research and CRIS Project No. 907-15-2, College of Agriculture, University of Kentucky, Lexington, Kentucky.

Bartsch, K. P., Miegroet H. Van, Boettinger J. and Dobrowolski, J. P. 2002. Using empirical erosion models models and GIS to determine erosion risk at Camp Williams, Utah. Journal of Soil and Water Conservation, 57, No.1, 29-36.

Bathurst, J. C., 2002. Physically-based erosion and sediment yield modeling: the

SHETRAN concept. In: Summer, W., Walling, D.E. (Eds.), Modeling Erosion, Sediment Transport and Sediment Yeild. IHP, UNESCO, Paris, France.

Beven, K.J., and Kirkby, M.J. 1979. A physical-based variable contributing area model of basin hydrology. Hydrol. Sci. Bull., 24, 43-69.

Bhuyan, S. J., Marzen, L. J., Koelliker, J. K., Harrington, J. A. and Barnes, P. L. 2002. Assessment of runoff and sediment yield using remote sensing, GIS, and AGNPS. Journal of Soil and Water Conservation, 57, No. 6, 351-364.

Bragadin, G.L., Franchini, M., Morgagni, A., Todini, E., 1993. Agricultural non-point source nutrient loadings estimated by means of an extended version of AGNPS. The Bidente-Ronco case study - Part I. INGEGNERIA AMBIENTALE, Vol.22, Nr.9, S. 455

Brigham, M. E., McCullough, and Wilkinson, P., 2001, Analysis of Suspended-Sediment Concentrations and Radioisotope Levels in the Wild Rice River Basin, Northweatern Minnesota, 1973-98, U.S. Geological Survey, Water-Resource Investigations Report 01-4192.

Burrough, PA. 1986, Principles of Geographic Information Systems for Land Resources Assessment, Clarendon Press, Oxford.

Chang, H. H. 1979, Geometry of rivers in regime, Journal of the Hydraulics Division American Society of Civil Engineers, 105, HY6, pp. 691-706.

Chavoshian, A., K. Takeuchi, H. Ishidaira, and Y. Hirabayashi. 2006. A blind test method for prediction in ungauged basin. Annual Journal of Hydraulic Engineering, JSCE, Vol. 50.

Chen, Ching-Nuo, Tsai, Chih-Heng and Tsai, Chang-Tai, 2006, Simulation of Sediment Yield from Watershed by Physiographic Soil Erosion-deposition Model, Journal of Hydrology, 327, P.293-303.

Chow, V. T., 1964. Open Channel Hydraulics. New York: McGraw-Hill.

Cohen, J. 1988. Statistical power analysis for the behavioral sciences (2nd ed.) Hillsdale, NJ: Lawrence Erlbaum Associates.

Daluz-Vieira, J. H. 1983. Conditions Governing the Use of Approximations for The Saint-Venant Equations for Shallow Surface Water Flow, Journal of Hydrology, 60, 43-58, 1983.

Das, G., Agarwal, A., 1990. Development of a conceptual sediment graph model. Transactions of ASAE 33, 100-104.

De Roo, A.P.J., Hazelhoff, L. and Burrough, P.A. 1989. Soil erosion modelling using 'ANSWERS' and Geographical Information Systems. Earth Surface Processes and Landforms, Vol. 14, 517-532. John Wiley & Sons Ltd.

Desmet, P. J. J. and Govers, G. 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. J. soil Wat. Conserv., 515, 427-433.

Engelund, F. and E. Hansen. 1967. A monograph on sediment transport in alluvial stream.

Teknisk Forlag, Copenhagen, Denmark, 65 p.

Enviromental System Research Institute. 2002. ArcView 3.X. ESRI, Redlands, California. URL: http://www.esri.com/software/arcview/. Accessed 2 April 2002.

Enviromental System Research Institute. 2003. Arc Hydro Tools-Tutorial v.1.1 beta 2. ESRI.

Enviromental System Research Institute. 2007. ArcGIS, http://www.esri.com/software/arcgis/

Environment Agency, 2002. Agriculture and natural resources: benefits, cost and potential solution. Environment Agency, Bristol.

Federal Emergency Management Agency (FEMA) 2006 (Landslide and Debris Flow (Mudslide) http://www.fema.gov/hazard/landslide/index.shtm)

Fernandez C., Wu, J. Q., McCool D. K. and Stockle, C. O. 2003. Estimating water erosion and sediment yield with GIS, RUSLE and SEDD. Journal of Soil and Water Conservation, 58, No.3, 128-136.

Ferris, Frank K, 1996, Handbook of Western reclamation techniques., Office of Technology Transfer, Western Regional Coordinating Center, Office of Surface Mining Reclamation and Enforcement, Denver, CO :

Ferro, Vito. 1998. Evaluating overland flow sediment transport capacity. Hydrological Processes, 12, 1895-1910

Flanagan, D.C., Nearing, M. A.(Eds.), 1995. USDA-Water Erosion Prediction Project hillslope profile and watershed model documentation, NSERL Report, vol. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana, USA.

Foster, G. R., L. J. Lane, J. D. Nowlin, J. M. Laflen and R. A. Young. 1980. : A model to estimate sediment yield from field-sized areas: Development of model. In: W. G. Knisel (ed.) CREAMS: A field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, U. S. Dept. of Agric., Sci. and Educ. Admin., Conser. Rep. No. 26. pp. 36-64.

Foster, G. R. and Lane, L. J., 1987, User requirement: USDA-Water Erosion Prediction Project (WEPP). NSERL Report No.1. West Lafayette: USDA-ARS National Soil Erosion Research Laboratory.

Foster, G.R., Lane, L.J., Nowlin, J.D., Laflen, J.M. and Young, R.A. 1981. Estimating erosion and sediment yield on field-size area. Transaction of the American Society of Agricultural Engineers 24:1253-63.

Foster. G. R., and L. D. Meyer, 1972, Transport of soil particles by shallow flow. Transactions of the American Society of Agricultural Engineers 15, 99-102.

Foster. G. R., and L. D. Meyer, 1975, Mathematical simulation of upland erosion using fundamental erosion mechanics, In Present and prospective technology for predicting sediment yields and sources, Washington, DC: US Department of Agriculture, Agricultural Research Sevice, pp. 190-207.

Frenette, M. and Julien, P. Y., 1987, Computer Modeling of Soil Erosion and Sediment

Yield from Large Watersheds, International Journal of Sediment Research, No. 1, p.39-68.

Gabet Emmanuel J. and Thomas Dunne, 2003, Sediment detachment by rain power, Water Resources Research, Vol. 39, No. 1, 1002.

Garbrecht, J. and Martz LW. 2000. TOPAZ: an automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization: overview. ARS-NAWQL 95-1, USDA-ARS, Durant, OK. URL:http://grl.ars.usda.gov/topaz/TOPAZ1.HTM. Accessed 28 June 2000.

Garde, R. J., Rangaraju, K. C., Swamee, P. K., Miraki, G. D., and Molaanezhed, M. 1983. Mathematical modeling of sedimentation process in reservoirs. Hydraulic Engineering, report No. HYD 8304. University of Rookee, India.

Gilbert, K. G., 1914, The transportation of debries by running water, U.S. Geological Survey Professional Paper 86, 263p.

Gilley, JE, Woolhiser, DA, and McWhorter, DB, 1985, Interrill Soil Erosion - Part I: Development of Model Equations, Transactions of the American Society of Agricultural Engineers Vo. 28, No. 1, p 147-153 and 159.

Govers. G. 1985. Selectivity and transport capacity of thin flows in relation to rill generation. Catena, 12, 35-49.

Govers, G. 1992. Evaluation of transporting capacity formulae for overland flow, in Parsons, J. and Abrahams, A. D. (eds), Overland Flow. Pp.243-274.

Govers, G., and G. Rauws 1986. “Transporting Capacity of Overland Flow on Plane and on Irregular Beds,” Earth Surface Processes and Landforms, vol. 11, pp. 515-524.

Graf, W. H., 1971, Hydraulics of Sediment Transport. New York: McGraw-Hill.

Green WH, Ampt GA. 1911. Studies on soil physics: 1.Flow of air and water through soils. Journal of Agricultural Science 4: 1-24.

Gregory, J.M. 1982. Soil cover prediction with various amounts and types of crop residue. Trans. ASAE 25:1333-1337.

Guy, B.T., Dickinson, W.T. and Rudra, R.P., 1987, The roles of rainfall and runoff in the sediment transport capacity of interrill flow, Soil and Water Div. of ASAE, No. 86-2537,pp 1378-1386.

Guy, B. T. and W. T. Dickinson, 1990, Inception of sediment transport in shallow overland flow, In Soil Erosion-Experiment and Models, 91-109, Ed., R. B. Bryan Catena Supplement 17. Cremlingen: Springer-Verlag.

Guy, B. T., Dickinson, W. T. and Pudra, R. P. 1990. Hydraulics of sediment-laden sheetflow and the influence of simulated rainfall. Earth Surface Processes and Lanforms, vol. 15, 101-118.

Guy, B.T., Rudra, R.P. and Dickinson, W.T., 1992, Process-oriented research on soil erosion and overland flow. Overland Flow Hydraulic and Erosion Mechanics, Edited by Anthony J, Parsons and Athol D. Abrahams, Chapman and Hall, New York.

Hall, Graham and Cratchley, Roger, 2006, Sediment erosion, transport and deposition during the July 2001 Mawddach extreme flood event, Processing paper, 2nd Sino-American Workshop on Advanced Computational Modeling in Hydroscience & Engineering, Beijing, China.

Hairsine, P. B. and Rose, C. W. 1992a. Modeling water erosion due to overland flow using physical principles 1. Sheet Flow. Water Resources Research, 28, No. 1, 237-243.

Hairsine, P. B. and Rose, C. W. 1992b. Modeling water erosion due to overland flow using physical principles 2. Rill Flow. Water Resources Research, 28, No. 1, 245-250.

Holmgren, P. 1994. Multiple flow direction algorithms for runoff modeling in grid based elevation models: An empirical evaluation. Hydrological Processes, 8, 327-334.

Horton, R. E. 1935. "Surface Runoff Phenomena; Part I, Analyses of the Hydrograph," Hydrology Laboratory, Pub 101, Edwards Feathers, Inc. Ann Arbor, MI.

Hrissanthou, Vlassios, 2005. Estimate of sediment yield in a basin without sediment data, Catena, 64, 333-347.

International Soil Reference and Information Centre, 2007, Global Assessment of Human-induced Soil Degradation (GLASOD), http://www.isric.org/UK/About+ISRIC /Projects/Track+Record/GLASOD.htm

Jain, S. K., Kumar, S.V. and Varghese, J. 2001. Estimation of Soil Erosion for a

Himalayan Watershed Using GIS Technique. Water Resources Management, 15, 41-54.

Jain, M. K. and Kothyari, U. C. 2000. Estimation of soil erosion and sediment yield using GIS. Hydrol. Sci. J. 45(5), 771-786.

Jain, Sanjay K. and Goel, M. K. 2002. Assessing the vulnerability to soil erosion of the Ukai Dam catchments using remote sensing and GIS. Hydrological Sciences, 47(1), 31-40.

Johnson, B. E., 1997, Development of A storm Event Based Two-Dimensional Upland Erosion Model, PhD Dissertation, Colorado State University, Fort Collins.

Johnson, B. E., Julien, Y. J., Molnar, D. K. and Watson, C. C. 2000, The 2-D upland erosion model CASC2D-SED. Journal of The American Water Resources Association, Vol. 36, No. 1.

Julien P. Y. and Frenette, M. 1985, Modeling of rainfall erosion, Journal of Hydraulic Engineering, Vol. 111, No. 10, P.1344-1359.

Julien, P. Y. and Simons, D. B. 1985. Sediment transport capacity of overland flow. American Society of Agricultural Engineers, 28, No. 3, 755-762.

Julien, P. Y, 1994, Erosion and Sedimentation, Cambridge University Press, UK

Julien, P. Y. , Saghafian B. and Ogden, F. L. 1995. Raster-based hydrologic modeling of spatially-varied surface runoff. Water Resource Bull, 31(3), 523-536.

Julien, Pierre and Rojas, Rosalia, 2002, Upland erosion modeling with CASC2D-SED, International Journal of Sediment Research, Vol. 17, No. 4, pp 265-274.

Julien, P.Y., 2002, River Mechanics. Cambridge University Press, UK.

Kalin, L., 2002, Sediment Source Area Identification Over Watershed: Influence of Spatial Scale and Sediment Travel Times, Ph.D. Dissertation, Purdue University.

Kalin, L., Govindaraju, R.S. and Hantush, M. M. 2003. Effect of geomorphologic resolution on modeling of runoff hydrograph and sedimentograph over small watersheds. Journal of Hydrology, 276, 89-111.

Kalin, L. and Hantush, M. M. 2003. Evaluation of sediment transport models and comparative application of two watershed models. EPA/600/R-03/139, National Risk Management Research Laboratory Office of Research and Development, US EPA.

Kibler DF, Woolhiser DA. 1970. The Kinematic Cascade as A Hydrologic Model. Hydrology Paper 39. Colorado: Colorado State University.

Kilinc, M.Y., 1972, Mechanics of soil erosion from overland flow generated by simulated rainfall. Ph.D. dissertation, Colorado State University, Fort Collins, 183 p.

Kilinc, M., and E. V. Richardson, 1973. "Mechanics of Soil Erosion from Overland Flow Generated by Simulated Rainfall," Hydrology papers no. 63, Colorado State University, Fort Collins, Colorado, 80523.

Klemes, V. 1986. Operational testing of simulation models, Hydrological Science Journal, Vol. 33, pp. 13-24.

Kothyari, Umesh C., Jain, Manoj K. and Raju, Kittur G. 2002. Estimation of temporal variation of sediment yield using GIS. Hydrological Sciences, 47(5), 693-706.

Kramer, L.A., Alberts, E.E., Hjelmfelt, A.T., and Gebhardt, M.R. 1990. Effect of soil conservation systems on groundwater nitrate levels from three corn-cropped watersheds in southwest Iowa, In J. Lehr (ed.) Proc. of the 1990 Cluster of Conferences, Kansas City, MO, 20-21 Fed. 1990, Nat. Ground Water Assoc., Westerville, OH, 175-189.

Kumar, S., Rastogi, R.A., 1987. Aconceptual catchment model for estimating suspended sediment flow. Journal of Hydrology 95, 155-163.

LESAM (Landscape-based Environmental System Analysis & Modeling) Lab, 2007, http://lesam.geog.buffalo.edu/lesam/

Leopold, Luna B., Wolman, M. Gordon and Miller, John P., Fluvial Processes in Geomorphology, W. H. Freeman and Company, 1986.

Leopold, L.B., Wolman, M. G. and Miller, J.P. 1964. Fluvial processes in geomorphology. Freeman, San Francisco.

Li, R. M. and H. W. Shen, 1973, Effect of tall vegetation on flow and sediment, J. Hydraulic. Div., ASCE, 99(5).

Line, D.E. and Foster, M.A., 1996. User's Manual for the Watershedss GRASS-AGNPS Modeling Tool, NCSU Water Quality Group, Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, NC 27695

Low, H. S. 1989. Effect of sediment density on bed-load transport, Proc. ASCE, 115, 124-138.

MacCormack, R. W., 1971, Numerical solution of interaction of shock wave with laminar boundary layer, Lecture notes in physics, Spring-Verlag, 8, 151-163.

Maidment, D. R., Olivera F., Calver, A., Eatherall, A. and Fraczek, W. 1996. Unit hydrograph derived from a spatially distribution velocity field. Hydrol Process, 10(6), 831-844.

McCool, D. K., Foster, G. R., Mutchler, C. K. and Meyer, L. D. 1989. Revised slop length factor for the Universal Soil Loss Equation. Trans. Am. Soc. Agric. Engrs, 32, 1571-1576.

McCuen, Richard H., 1992, Microcomputer Applications in Statistical Hydrology, PTR PRENTICE HALL, Englewood Cliffs, New Jersey.

Mein R.G. and C.L. Larson. 1973. Modeling infiltration during a steady rain. Water Resour. Res. 9(2): 384-394.

Merten, G. H., Nearing, M. A. and Borges, A. L. O., 2001, Effect of sediment load on soil detachment and deposition in rills, Soil Sci. Soc. Am. J., 65, PP. 861-868.

Meyer M M and Perry D A 1979 Ectomycorrhizal populations on a chronosequence of disturbed areas in the central Cascades. In Abstr. 4th N. Amer.Conf. on Mycorrhizae. Ed. C P P Reid. p 101. Colorado State University, Fort Collins.

Molnar, D. K. and Julien, P.Y. 1998. Estimation of upland erosion using GIS. Computers and Geosciences, 24, No. 2, 183-192.

Moore, R.J., 1984. A dynamic model of basin sediment yield. Water Resources Research 20, 89-103.

Moore, I. D. and Burch, G. J. 1986. Sediment Transport Capacity of Sheet and Rill Flow: Application of Unit Stream Power Theory. Water Resources Research, 22, No. 8, 1350-1360.

Moore, I. D. and Wilson, J. P. 1992. Length slope factor for the Revised Universal Soil Loss equation: simplified method of solution. J. Soil Wat. Conserv. 47(5), 423-428.

Moore, I. D., Gessler, P. E., Gessler, P. E., Nielsen, G. A. and Peterson, G. A. 1992. Terrain analysis for soil-specific crop management, in soil Specific Crop Management: A Workshop on Research and Development Issues. Minnesota Extension Service, University of Minnesota (Agriculture), Minneapolis. 23 pp.

Moore, I. D., Turner, A. K. Wilson, J. P., Jenson, S. K. and Band, L. E. 1993. "GIS and land-surface-subsurface process modeling" in Goodchild. M. F., Parks, B. O. and Steyaert, L. T. (eds), Environmental modeling with GIS, 213-230.

Morgan, R.P.C., Quinton, J.N., Smith, R.E., Gover, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., Styczen, M.E., 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms 23, 527-544.

Morgan, R.P.C., 2005, Soil Erosion and Conservation, Third Edition, Blackwell Publishing Ltd., MA. USA.

Moss, A. J. 1979, Thin-flow transportation of solids in arid and non-arid area: A comparison of processes, IAHS-AISH Publ., 128, 435-445.

Natural Resources Conservation Service (NRCS), 2007, http://www.mo15.nrcs.usda.gov /features/gallery/gallery.html.

Nash, J.E. and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models. I. Discussion of principles. Jpurnal of Hydrology 10: 282-90.

O'Brien, J. S. 2006. FLO-2D Users Manual, FLO-2D Software, Inc., Arizona, U.S.A.

Ogden, F.L. and Julien, P.Y. 2002 CASC2D: A two-dimensional, physically-based, hortonian, hydrologic model. In: Mathematical Models of Small Watershed Hydrology and Applications, V.J. Singh and D. Freverts, eds., Water Resources Publications, Littleton, CO, ISBN 1-887201-35-1, 922pp.

Oldeman, L. R. 1991: Global extent of soil degradation. ISRC Annual Report. Wageningen.

Orlandini, S., and R. Rosso. 1996. Diffusion wave modeling of distributed catchment dynamics, J. Hydrol. Eng. Am. Soc. Civ. Eng., 1, 103 – 113.

Paringit, Enrico C. and Nadaoka, Kazuo. 2003. Sediment yield modeling for small agricultural catchments: land-cover parameterization based on remote sensing data analysis. Hydrological Processes, 17,1845-1866.

Pearce, A. J. 1976. Magnitude and frequency of erosion by Hortonian overland flow. Journal of Geology 84:65-80.

Pierce, E.J., Larson, W.E., and Dowdy, R.H. 1986. Filed estimates of C factor: How good are they and how do they affect calculations of erosion?, Soil Conservation Asseesing the National Resources Inventory, Vol. 2, Committee on Conservation Need and Opportunities Board on Agriculture National Research Council, National Academy Press, Washington,D.C.

Pimental, D., Allen, J., Beers, A., Guinand, L., Hawkins, A., Linder, R., McLaughlin, P., Meer, B., Musonda, D.,Perdue, D., Poisson, S., Salazar, R., Siebert, S. and Stoner, K. 1993. Soil erosion and agricultural productivity. In Pimental, D. (ed.), World soil erosion and conservation. Cambridge University Press, Cambridge:277-92.

Potter, Merle C. and Wiggert, David C., 1991. Mechanics of Fluids, Prentice Hall.

Prosser Ian P. and Paul Rustomji, 2000, Sediment transport capacity relations for overland flow, Progress in Physical Geography, 20,2, pp. 179-193.

Quinn, P., Beven, K., Chevallier, P., and Planchon, O. 1991. The Prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. Hydrol. Process., 5, 59-79.

Quinton, J.N. 1997. Reducing predictive uncertainty in model simulations: a comparison of two methods using the European Soil Erosion Model (EUROSEM). Catena 30: 101-17.

Rauws, G., 1984, De Transportcapacitit Afterflow Over Een Ruw Oppervlak: Laboratoriumexperimenten. Licentiaatsthesis KUL. Fac. Wet., Leuven, 127pp.

Rawls, W.J., and D.L.Brakensiek. 1983. A proceedure to predict Green and Ampt. infiltration parameters. In Advances in infiltration. Proc. of the Nat'l Conference on Advances in Infiltration. Dec. 12-13. Chicago, IL.

Renard, K. G., Foster, G. R., Weesies, G. A. and Porter, J. P. 1991. RUSLE, Revised Universal Soil Loss Equation. J. Soil Wat. Conserv. 46(1), 30-33.

Renschler CS. 2001. GeoWEPP-the geo-spatial interface for the water erosion prediction project WEPP. URL: http://www.geog.buffalo.edu/~rensch/geowepp. Accessed 1 November 2001.

Renschler, Chris S. 2003. Designing geo-spatial interface to scale process models: the GeoWEPP approach. Hydrological Processes, 17, 1005-1017.

Rojas, R. 2002. GIS-based upland erosion modeling, geovisualization and grid size effects on erosion simulations with CASC2D-SED. PhD thesis, Dept. Civil Engr., Colorado State University, Fort Collins, Colorado.

Santos, C.A.G., Suzuki, K., Watanabe, M., Srinivasan, V.S., 1997. Developing a sheet erosion equation for a semiarid region. In: Walling, D.E., Probst, J.L. (Eds.), Proceedings of the International Symposium on Human Impact on Erosion Sedimentation, IAHS Publication, vol. 245, pp. 31-38. Rabat, Morocco.

Schmidt, J., 1993, Modeling long-term soil loss and landform change, in Overland Flow: Hydraulic and Erosion Mechanics, edited by A. J. Parsons.

Sekhar, K. R. and Rao, B. V. 2002. Evaluation of sediment yield by using remote sensing and GIS: a case study from the Phulang Vagu watershed, Nizamabad District (AP), India. International Journal of Remote Sensing, 23, No. 20, 4499-4509.

Sharma K.D. and Correia J. F. 1987. Short communication: An upland soil erosion model derived from the basic principles. Earth Surface Processes and Landforms, Vol. 12, 205-210.

Shen, H.W. and Li, R. M., 1973. Rainfall effect on sheet flow over smooth surface., J. Hydraul. Div. ASCE 99 (HYS), 771-792.

Shields, A. 1936. Anwendung der Ahnlichkeitsmechanik und turbulenz forschung auf die geschiebebewegung. Mitteil Preuss, Versuchsanst Wasser und Schiffsbau, Berlin No. 26. Translated to English by W. P. Ott and J.C. van Uchelen, Calif. Inst. Of Tech.

Silburn, D. M. and Loch, R. J., 1989, Evaluation of CREAMS MODEL. I. Sensitivity Analysis of the Soil Erosion/ Sedimentation Component for Aggregated Clay Soils, Aust. J. Soil Res., 27, 545-561.

Singh,V.P. 1995. Computer Models of Watershed Hydrology. Rev. ed. Highlands Ranch, CO: Water Resources Publications.

Singh, Vijay P., Yang, Chih Ted and Deng, Z. Q. 2003. Downstream hydraulic geometry relations: 1. Theoretical development. WATER RESOURCES RESEARCH, VOL. 39, NO. 12, 1337.

Smith, J.H., Davis, J.R., Fogel, M., 1977. Dtermination of sediment yield by transferring rainfall data. Water Resources Bulletin 13, 529-541.

Smart, G. M. 1984, Sediment transport formula for steep channels. Journal of Hydraulic Engineering, 110, P267-77.

Stuebe, M.M. and Johnston D.M. 1990. Runoff volume estimation using GIS techniques. Water Resource Bull, 26(4), 611-620.

Tarboton, D.G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research, 33(2), 309-319.

Tarboton, David G. 2002. Terrain Analysis Using Digital Elevation Models (TauDEM). Utah State University, http://www.engineering.usu.edu/dtarb/.

Tayfur, Gokmen and Singh, Vijay P., 2004, Numerical model for sediment transport over nonplanar, nonhomogeneous surface, J. of Hydrologic Eng., Vol. 9, Iss. 1, PP. 35-41.

United States Department of Agriculture, 1993, Soil Survey Manual.

US Army Corps of Engineers (USACE), 1998. HEC-RAS, River Analysis System: Hydraulic Reference Manual, Version 2.2. Hydrologic Engineering Center.

Uri, N.D. and Lewis, J.A. 1998. The dynamics of soil erosion in US agriculture. Science of the Total Environmenta 218, 45-58.

Van der Tak, L.D., and R.L. Bras,.1990. AIncorporating Hillslope Effects into the Geomorphological Instantaneous Unite Hydrograph, Water Resour. Res., 26(1):2393-2400.

Vanoni, V. A. 1978. Predicting sediment discharge in alluvial channels, Water Supply and Management, Pergamon Press, Oxfprd, pp. 399-417.

Vertessy, R. A., Wilson, C. J., Silburn, D. M., Connolly, R. D. and Ciesiolka, C. A. 1990. Predicting erosion hazard area using digital terrain analysis. Proceeding IAHS International Symposium on Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steepland, Suva, Fiji, 11-15.

Vieux, B.E. and Gauer, N. 1994. Finite element modeling of storm water runoff using GRASS GIS. Microcomput Civil Eng, 9, 263-270.

Waters, T. F., 1995, Sediment in streams-Sources, biological effects and control: American Fisheries Society Monograph 7: Bethesda, Maryland, American Fisheries Society, 251 p.

Ward, Andy D. and Trimble, Stanley W., 2004, Environmental Hydrology, Second Edition, Lewis Publishers, 462 pp.

Weibull, W. 1951, A statistical distribution function of wide applicability, Journal of Applied Mechanics,Transactions of ASME, Vol. 18, No.3, pp.293-297.

Williams, J.R. 1975. Sediment routing for agricultural watersheds. Water Resources Bulletin. 11(5):965-974.

Williams, J. R. 1978. A sediment graph model based on instantaneous unit sediment graph. Wat. Resour. Res. 14(4), 659-664.

Wischmeier, W. H. and Smith, D. D. 1978. Predicting rainfall erosion losses. Agriculture Handbook no. 537, US Dept of Agriculture, Science and Education Administration.

Wolock, D. M. and McCabe, G. J., Jr., (1995), "Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL," Water Resources Research, 31(5), pp. 1315-1324

Yalin, M. S. 1963, An expression for bed-load transportation, Proc. ASCE, 105, 1433-1443.

Yalin, M.S. 1977. Mechanics of sediment transport. Pergamon Press, Second Ed., 112-165.

Yang, C. T. 1972, Unit stream power and sediment transport, Journal of the Hydraulics Division, ASCE, vol. 98, No. HY10, 1805-1826.

Yang, C. T. 1973. "Incipient Motion and Sediment Transport," Journal of the Hydraulics Division, ASCE, vol. 99, no. HY10, pp. 1679-1704.

Yang, C. T. 1976. Minimum Unit Stream Power and Fluvial Hydraulics, Journal of the Hydraulics Division, ASCE, vol. 105, No. HY7, Proceeding Paper 14677, 769-784.

Yang, C. T. 1979. Unit stream power equations for total load, Journal of Hydrology, vol. 40, pp. 123-138.

Yang, C. T. 1996a. Sediment Transport Theory and Practice. The McGraw-Hill Companies, Inc.

Yang, C. C. 1996b. Numerical simulation of hillslope soil erosion, M.S. degree thesis, Department of Harbor and River Engineering, National Taiwan Ocean University.

Young, R.A. 1989. AGNPS:A nonpoint source pollution model for evaluating agricultural watershed. Journal of Soil and Water Conservation, 44(2): 168-173

Appendix A

Table of sources of ε and β values from previous studies

Table A.1.Sources of ε and β values

Author	Equations/Models	ε	β	Data Type
Empirical Studies				
Band, 1985	$C_s \propto q^{1.07} S^{0.84}$	1.07	0.84	P
Everaert, 1991	$C_s \propto q^{0.10} S^{1.90}$	0.10	1.90	F
Everaert, 1991	$C_s \propto q^{0.19} S^{1.94}$	0.19	1.94	F
Everaert, 1991	$C_s \propto q^{0.36} S^{1.96}$	0.36	1.96	F
Everaert, 1991	$C_s \propto q^{0.79} S^{1.77}$	0.79	1.77	F
Everaert, 1991	$C_s \propto q^{1.18} S^{2.96}$	1.18	2.96	F
Everaert, 1991	$C_s \propto q^{0.47} S^{1.87}$	0.47	1.87	F
Everaert, 1991	$C_s \propto q^{2.10} S^{2.81}$	2.10	2.81	F
De Ploey, 1984	$C_s \propto q^{-0.375} S^{1.25}$	-0.38	1.25	L
Govers, 1985	$C_s \propto (Vu_*)^{1.5}$	1.58	1.73	F
Govers, 1990	$C_s \propto q^{0.65} S^{2.62}$	0.65	2.62	F
Govers, 1990	$C_s \propto q^{0.55} S^{2.76}$	0.55	2.76	F
Govers, 1990	$C_s \propto q^{0.70} S^{2.50}$	0.70	2.50	F
Govers, 1990	$C_s \propto q^{0.53} S^{1.97}$	0.53	1.97	F
Govers, 1990	$C_s \propto q^{0.73} S^{1.76}$	0.73	1.76	F
Govers, 1990	$C_s \propto q^{0.66} S^{1.44}$	0.66	1.44	F
Govers, 1990	$C_s \propto q^{0.80} S^{1.69}$	0.80	1.69	F
Govers, 1990	$C_s \propto q^{0.50} S^{1.96}$	0.50	1.96	F
Govers, 1990	$C_s \propto q^{0.24} S^{1.71}$	0.24	1.71	F
Govers, 1990	$C_s \propto q^{0.04} S^{1.47}$	0.04	1.47	F
Govers, 1991	$C_s \propto q^{0.75} S^{1.45}$	0.75	1.45	F
Kilinc, 1972	$C_s \propto q^{1.03} S^{1.66}$	1.03	1.66	L
Kilinc, 1972	$C_s \propto q^{0.93} S^{1.31}$	0.93	1.31	L
Komura, 1983	$C_s \propto q^{0.38} S^{1.50}$	0.38	1.50	F
Meyer and Monke, 1965	$C_s \propto D^{-0.5} q^{0.90} S^{3.50}$	0.90	3.50	F
Meyer and Wischmeier, 1969	$C_s \propto q^{0.67} S^{1.67}$	0.67	1.67	P
Musgrave, 1947	$C_s \propto L^{0.37} ; q_s \; S^{1.90}$	0.37	1.35	P
Rennard et al., 1997	$C_s \propto L^b (10.8S + 0.03), b = f(S)$	0.22	1.00	P
Rennard et al., 1997	$C_s \propto L^b (10.8S + 0.03), b = f(S)$	0.67	1.00	P

Author	Equations/Models	ε	β	Data Type
Wischmeier, 1978	$C_s \propto L^{0.2}(65.41S^2 + 4.56S + 0.065)$	0.20	1.56	P
Wischmeier, 1978	$C_s \propto L^{0.5}(65.41S^2 + 4.56S + 0.065)$	0.50	1.56	P
Young and Mutchler, 1969	$C_s \propto q^{0.24} S^{0.74}$	0.24	0.74	P
Zingg, 1940	$C_s \propto q^{0.60} S^{1.40}$	0.60	1.40	P
Kilinc, 1972	$q_s = e^{0.122}\left[(\tau_0 - \tau_c)V\right]^{1.67}$	0.67	1.67	P
Kilinc, 1972	$q_s = e^{-3.17} V^{-3.625}$	1.42	1.21	P
Kilinc, 1972	$q_s = e^{1.24} V^{-4.67} \mathrm{Re}^{-0.878}$	1.42	1.56	P
Kilinc, 1972	$q_s = e^{-11.6} \mathrm{Re}^{2.05} S^{1.46}$	1.05	1.46	P
Wischmeier and Smith, 1978	$q_s \sim L^{1.5}(.00076S^2 + .0053S + .0076)$	0.50	1.70	P
Li et al., 1973	$q_s = \alpha \int_0^L \tau_0^2 dx$	0.67	1.33	M
Unit Stream Power				
Govers and Rauws, 1986	$C_s \propto q^{0.67} S^{1.33}$	0.67	1.33	F
Huang, 1995	$C_s \propto \phi^{1.05}$	0.42	1.35	L
Huang, 1995	$C_s \propto \phi^{0.64}$	0.26	0.83	L
Huang, 1995	$C_s \propto \phi^{0.73}$	0.29	0.95	L
Huang, 1995	$C_s \propto \phi^{0.30}$	0.12	0.40	L
Moore and Burch, 1986a	$C_s \propto (\phi - 0.07)^{1.36}$	0.34	1.87	L
Slattery and Bryan, 1992	$C_s \propto \phi^{2.65}$	1.06	3.52	L
Slattery and Bryan, 1992	$C_s \propto \phi^{2.65}$	0.67	3.66	L
Stream Power				
Abrahams et al., 1998	$C_s \propto (qS - qs_c)^{1.73} d_s^{-1.212}$	0.01	2.09	F
Jayawardena and Bhuiyan, 1999	$C_s \propto (qS - qS_c)^{1.52} d_s^{-0.68}$	0.20	1.85	L
Slattery and Bryan, 1992	$C_s \propto (qS)^{1.66}$	0.66	1.66	L
Shear Stress				
Lu et al., 1989	$C_s \propto \tau_0^{1.27} d_s^{0.64}$	-0.24	0.89	F
Lu et al., 1989	$C_s \propto \tau_0^{1.46} d_s^{0.73}$	-0.12	0.51	F

Author	Equations/Models	ε	β	Data Type
Jayawardena and Bhuiyan, 1999	$C_s \propto u_*^{5.46}$	0.64	1.91	L
Slattery and Bryan, 1992	$C_s \propto u_*^{7.0}$	1.10	2.45	L
Sed. Erosion Model				
Beadley et al., 1980		-0.50	1.00	M
Beadley et al., 1980		1.00	1.00	M
Foster et al., 1995		-0.10	1.05	M
de Roo et al., 1995		0.22	0.78	M
Yu et al., 1997		0.40	1.30	M
Morgan et al., 1998		-0.22	0.73	M
Ahnert, 1987		-0.50	0.50	M
Kirkby, 1993		1.00	1.00	M
Howard, 1994		0.50	2.00	M
Thcker and Slingerland, 1997		0.00	1.00	M

Note: Data Type F means data collected from flume. Data Type L means data collected from laboratory plot. Data Type P means data collected from field plot. There is no data information for Type M.

Appendix B

Basic equations of Kinematic wave and Diffusive wave

For fully turbulent flows, analytic solutions of overland flow hydraulics are explained herein.

-Kinematic wave:

The momentum equation of kinematic wave is

$$S_0 = S_f \tag{B.1}$$

Manning equation for overland flow can be expressed as

$$V = \frac{1}{n} h^{2/3} S_0^{0.5} \tag{B.2}$$

By combining those governing equations, Eqs (B.1) and (B.2) into Eq. (3.19), the equation of kinematic wave routing can be derived as

$$\frac{\partial h}{\partial t} + \alpha h^{\beta} \cdot \beta h^{-1} \frac{\partial h}{\partial x} = i - f_i \tag{B.3}$$

where $\alpha = \frac{S_f^{\ 0.5}}{n}$ and $\beta = \frac{5}{3}$ using Manning equation. The equation can be simplified to

$$\frac{\partial h}{\partial t} + \frac{\beta q}{h} \frac{\partial h}{\partial x} = i - f_i \tag{B.4}$$

Then, the analytic solution of kinematic wave routing is expressed as

$$\frac{\partial h}{\partial t} + c_k \frac{\partial h}{\partial x} = i - f_i \tag{B.5}$$

where c_k = kinematic wave celerity; and $c_k = \frac{\beta q}{h} = \beta V = \frac{5}{3} V$ using Manning equation

-Diffusive wave:

From Eq. (3.18), the momentum equation of diffusive wave is

$$S_f = S_o - \frac{\partial h}{\partial x} \tag{B.6}$$

The flow resistance equation can be written in the following form.

$$q = K \cdot S_f^{0.5} \tag{B.7}$$

where K = the conveyance factor. Substitute S_f of Eq (B.7) to Eq. (B.6), the flow resistance equation can be expressed as

$$\frac{q^2}{K^2} = S_0 - \frac{\partial h}{\partial x} \tag{B.8}$$

Take a differential derivation with respect to time on both sides, it becomes

$$\frac{2q}{K^2}\frac{\partial q}{\partial t} - \frac{2q^2}{K^3}\frac{\partial K}{\partial t} = -\frac{\partial^2 h}{\partial x \partial t} \tag{B.9}$$

The flow continuity equation for unit width can be expressed as

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_e \tag{B.10}$$

where i_e = excesses rainfall, ($i - f_i$). Take a differential derivation with respect to distance in the continuity equation. Eq. (B.10) becomes

$$\frac{\partial^2 h}{\partial x \partial t} + \frac{\partial^2 q}{\partial x^2} = 0 \tag{B.11}$$

By eliminating $\frac{\partial^2 h}{\partial x \partial t}$ from Eqs. (B.11) and (B.9), we obtain

$$-\frac{2q^2}{K^3}\frac{\partial K}{\partial t}+\frac{2q}{K^2}\frac{\partial q}{\partial t}+\frac{\partial^2 q}{\partial x^2}=0 \tag{B.12}$$

By multiplying Eq. (B.12) with $\frac{K^2}{2q}$,

$$-\frac{q}{K}\frac{\partial K}{\partial t}+\frac{\partial q}{\partial t}+\frac{K^2}{2q}\frac{\partial^2 q}{\partial x^2}=0 \tag{B.13}$$

Based on the chain rule, we may write that $\frac{\partial K}{\partial t}=\frac{dK}{dh}\frac{\partial h}{\partial t}$. Substitution for $\frac{\partial h}{\partial t}$ from Eq. (B.10) into $\frac{\partial K}{\partial t}=\frac{dK}{dh}\frac{\partial h}{\partial t}$ gives

$$\frac{\partial h}{\partial t}=-\frac{\partial q}{\partial x}+i_e \tag{B.14}$$

$$\frac{\partial K}{\partial t}=\left.\frac{dK}{dh}\right|_{x=x_0}\left(-\frac{\partial q}{\partial x}+i_e\right) \tag{B.15}$$

To simplify the derivation, let us obtain the derivative dK/dh from the expression $q=K\cdot S_0^{0.5}$ for uniform flow instead of from the general expression $q=K\cdot S_f^{0.5}$. From Eq. (B.15) the following equation is derived:

$$\frac{\partial K}{\partial t}=\frac{1}{S_0^{\ 0.5}}\left(\frac{dq}{dh}\right)\left(\frac{-\partial q}{\partial x}+i_e\right) \tag{B.16}$$

and Eq. (B.13) becomes to

$$-\frac{q}{K}\frac{\partial K}{\partial t}+\frac{\partial q}{\partial t}+\frac{q}{2S_0}\frac{\partial^2 q}{\partial x^2}=0 \tag{B.17}$$

By eliminating $\frac{\partial K}{\partial t}$ from Eqs. (B.16) and (B.17), we can obtain

$$\left[\frac{q}{K}\frac{1}{S_0^{0.5}}\frac{dq}{dh}\right]\left[\frac{\partial q}{\partial x}-i_e\right]+\frac{\partial q}{\partial t}+\frac{q}{2S_0}\frac{\partial^2 q}{\partial x^2}=0 \qquad \text{(B.18)}$$

By simplifying the resulting equation, we obtain

$$\left[\frac{dq}{dh}\right]\left[\frac{\partial q}{\partial x}-i_e\right]+\frac{\partial q}{\partial t}+\frac{q}{2S_0}\frac{\partial^2 q}{\partial x^2}=0 \qquad \text{(B.19)}$$

$$\frac{\partial q}{\partial t}+\frac{dq}{dh}\frac{\partial q}{\partial x}+\frac{q}{2S_0}\frac{\partial^2 q}{\partial x^2}=\frac{\partial q}{\partial h}\cdot i_e \qquad \text{(B.20)}$$

By dividing by flow velocity, we obtain

$$\frac{\partial h}{\partial t}+\frac{dq}{dh}\frac{\partial h}{\partial x}+\frac{q}{2S_0}\frac{\partial^2 h}{\partial x^2}=i_e \qquad \text{(B.21)}$$

Eq. (B.21) can also be expressed as

$$\frac{\partial h}{\partial t}+c_d\frac{\partial h}{\partial x}+D\frac{\partial^2 h}{\partial x^2}=(i-f_i) \qquad \text{(B.22)}$$

where c_d = the diffusive wave celerity defined as $c_d=\frac{dq}{dh}=\beta V$. $\beta=\frac{5}{3}$ using Manning equation. D = the hydraulic diffusivity defined as $D=\frac{q}{2S_0}$. The term of $D\frac{\partial^2 h}{\partial x^2}$ represents the diffusion of a flood wave as it travels on overland surface. It can be disregarded when the bed slope is steep, or flow depth is shallow. Then, remaining equation of Eq. (B.22) is expressed as

$$\frac{\partial h}{\partial t}+c_d\frac{\partial h}{\partial x}\cong(i-f_i) \qquad \text{(B.23)}$$

This is the same as the equation for kinematic wave routing in Eq. (B.5)

Appendix C

Published Overland Flow Erosion Experimental Data

Table C.1 Published Overland Flow Erosion Experimental Data.

Data Source	Data ID	Flume Length (*m*)	d_{50} (*mm*)	Slope (*m/m*)	Rainfall intensity (*mm/hr*)	Unit Discharge (m^2/s)	Flow Depth (m*m*)	Flow Velocity (*m/s*)	Con. (*mgl*)	Darcy-Weisbach Friction *f*	Manning Roughness n_o
A	1	3.66	0.3	0.03	0.0	0.001647	4.9	0.34	15446	9.9	0.015
A	2	3.66	0.3	0.03	0.0	0.002279	5.6	0.40	20894	12.3	0.014
A	3	3.66	0.3	0.03	0.0	0.003146	7.8	0.40	31217	9.0	0.017
A	4	3.66	0.3	0.03	0.0	0.003877	8.2	0.47	36233	11.5	0.015
A	5	3.66	0.3	0.03	0.0	0.004732	8.5	0.55	42174	15.3	0.013
A	6	3.66	0.3	0.04	0.0	0.001647	4.0	0.42	22944	13.9	0.012
A	7	3.66	0.3	0.04	0.0	0.002279	6.1	0.37	37739	7.3	0.018
A	8	3.66	0.3	0.04	0.0	0.003146	6.6	0.48	45265	11.2	0.015
A	9	3.66	0.3	0.04	0.0	0.003877	7.8	0.50	55003	10.2	0.016
A	10	3.66	0.3	0.04	0.0	0.004732	8.4	0.56	58560	12.1	0.015
A	11	3.66	0.3	0.06	0.0	0.001647	4.1	0.40	42094	8.3	0.016
A	12	3.66	0.3	0.06	0.0	0.002279	5.3	0.43	84097	7.3	0.018
A	13	3.66	0.3	0.06	0.0	0.003146	5.8	0.54	98618	10.8	0.015
A	14	3.66	0.3	0.06	0.0	0.003877	7.0	0.55	112999	9.3	0.016
A	15	3.66	0.3	0.06	0.0	0.004732	8.1	0.59	137216	9.0	0.017
A	16	3.66	0.3	0.08	0.0	0.001647	3.8	0.43	79400	7.8	0.016
A	17	3.66	0.3	0.08	0.0	0.002279	4.7	0.48	112369	7.8	0.017
A	18	3.66	0.3	0.08	0.0	0.003146	5.8	0.54	111152	8.1	0.017
A	19	3.66	0.3	0.1	0.0	0.001647	3.5	0.47	127546	8.0	0.016

Data Source	Data ID	Flume Length (m)	d_{50} (mm)	Slope (m/m)	Rainfall intensity (mm/hr)	Unit Discharge (m^2/s)	Flow Depth (mm)	Flow Velocity (m/s)	Con. (mgl)	Darcy-Weisbach Friction f	Manning Roughness n_o
A	20	3.66	0.3	0.1	0.0	0.002279	4.1	0.55	176290	9.5	0.015
A	21	3.66	0.3	0.1	0.0	0.003146	4.7	0.67	197661	12.0	0.013
A	22	3.66	0.5	0.03	0.0	0.001647	5.2	0.32	11382	8.3	0.016
A	23	3.66	0.5	0.03	0.0	0.002279	6.9	0.33	13646	6.8	0.019
A	24	3.66	0.5	0.03	0.0	0.003146	7.8	0.40	15940	9.0	0.017
A	25	3.66	0.5	0.03	0.0	0.003877	10.2	0.38	19921	6.0	0.021
A	26	3.66	0.5	0.03	0.0	0.004732	10.5	0.45	22518	8.2	0.018
A	27	3.66	0.5	0.04	0.0	0.001647	4.9	0.34	21047	7.5	0.017
A	28	3.66	0.5	0.04	0.0	0.002279	5.8	0.39	27031	8.5	0.016
A	29	3.66	0.5	0.04	0.0	0.003146	7.6	0.41	35190	7.1	0.019
A	30	3.66	0.5	0.04	0.0	0.003877	7.2	0.54	38076	13.0	0.014
A	31	3.66	0.5	0.04	0.0	0.004732	7.9	0.60	38715	14.3	0.013
A	32	3.66	0.5	0.06	0.0	0.001647	4.3	0.39	38209	7.4	0.017
A	33	3.66	0.5	0.06	0.0	0.002279	5.2	0.44	45901	7.9	0.017
A	34	3.66	0.5	0.06	0.0	0.003146	5.8	0.54	52785	10.8	0.015
A	35	3.66	0.5	0.06	0.0	0.003877	6.4	0.61	60799	12.2	0.014
A	36	3.66	0.5	0.06	0.0	0.004732	8.5	0.55	79694	7.6	0.018
A	37	3.66	0.5	0.08	0.0	0.001647	4.0	0.42	57901	6.9	0.017
A	38	3.66	0.5	0.08	0.0	0.002279	4.9	0.47	93826	7.1	0.017
A	39	3.66	0.5	0.08	0.0	0.003146	5.8	0.54	96016	8.1	0.017
A	40	3.66	0.5	0.08	0.0	0.003877	6.4	0.61	116530	9.1	0.016
A	41	3.66	0.5	0.08	0.0	0.004732	7.2	0.66	81518	9.7	0.016

Data Source	Data ID	Flume Length (*m*)	d_{50} (*mm*)	Slope (*m/m*)	Rainfall intensity (*mm/hr*)	Unit Discharge (m^2/s)	Flow Depth (m*m*)	Flow Velocity (*m/s*)	Con. (*mgl*)	Darcy-Weisbach Friction *f*	Manning Roughness n_o
A	42	3.66	0.5	0.1	0.0	0.001647	4.0	0.42	66663	5.6	0.019
A	43	3.66	0.5	0.1	0.0	0.002279	4.4	0.52	95719	7.7	0.017
A	44	3.66	0.5	0.1	0.0	0.003146	5.3	0.59	106469	8.3	0.016
A	45	3.66	0.5	0.1	0.0	0.003877	5.9	0.65	115034	9.1	0.016
A	46	3.66	0.5	0.1	0.0	0.004732	6.7	0.71	139952	9.5	0.016
A	47	3.66	0.7	0.03	0.0	0.001647	5.2	0.32	12014	8.3	0.016
A	48	3.66	0.7	0.03	0.0	0.002279	6.4	0.36	12797	8.4	0.017
A	49	3.66	0.7	0.03	0.0	0.003146	7.6	0.41	16318	9.5	0.016
A	50	3.66	0.7	0.03	0.0	0.003877	9.3	0.42	18616	7.9	0.018
A	51	3.66	0.7	0.03	0.0	0.004732	9.6	0.49	20222	10.7	0.016
A	52	3.66	0.7	0.04	0.0	0.001647	5.2	0.32	14633	6.2	0.019
A	53	3.66	0.7	0.04	0.0	0.002279	6.6	0.35	17890	5.9	0.020
A	54	3.66	0.7	0.04	0.0	0.003146	7.5	0.42	25021	7.6	0.018
A	55	3.66	0.7	0.04	0.0	0.003877	8.4	0.46	30092	8.1	0.018
A	56	3.66	0.7	0.04	0.0	0.004732	9.9	0.48	35130	7.3	0.019
A	57	3.66	0.7	0.06	0.0	0.001647	4.9	0.34	34958	5.0	0.021
A	58	3.66	0.7	0.06	0.0	0.002279	6.7	0.34	45052	3.7	0.026
A	59	3.66	0.7	0.06	0.0	0.003146	7.2	0.44	49569	5.7	0.021
A	60	3.66	0.7	0.06	0.0	0.003877	7.8	0.50	53275	6.8	0.019
A	61	3.66	0.7	0.06	0.0	0.004732	8.1	0.59	61673	9.0	0.017
A	62	3.66	0.7	0.08	0.0	0.001647	4.7	0.35	60792	4.1	0.023
A	63	3.66	0.7	0.08	0.0	0.002279	5.8	0.39	75805	4.3	0.023

Data Source	Data ID	Flume Length *(m)*	d_{50} *(mm)*	Slope *(m/m)*	Rainfall intensity *(mm/hr)*	Unit Discharge *(m^2/s)*	Flow Depth (mm)	Flow Velocity *(m/s)*	Con. *(mgl)*	Darcy-Weisbach Friction f	Manning Roughness n_o
A	64	3.66	0.7	0.08	0.0	0.003146	6.2	0.50	84617	6.5	0.019
A	65	3.66	0.7	0.08	0.0	0.003877	7.5	0.52	101945	5.7	0.021
A	66	3.66	0.7	0.08	0.0	0.004732	7.8	0.61	120233	7.6	0.018
A	67	3.66	0.7	0.1	0.0	0.001647	4.3	0.39	106770	4.5	0.022
A	68	3.66	0.7	0.1	0.0	0.002279	5.2	0.44	124709	4.8	0.022
A	69	3.66	0.7	0.1	0.0	0.003146	5.8	0.54	121084	6.5	0.019
A	70	3.66	0.7	0.1	0.0	0.003877	7.0	0.55	138102	5.6	0.021
A	71	3.66	0.7	0.1	0.0	0.004732	7.6	0.62	153758	6.4	0.020
A	72	3.66	1.0	0.03	0.0	0.001647	6.1	0.27	5329	5.1	0.021
A	73	3.66	1.0	0.03	0.0	0.002279	7.0	0.33	8096	6.4	0.020
A	74	3.66	1.0	0.03	0.0	0.003146	9.1	0.34	8041	5.5	0.022
A	75	3.66	1.0	0.03	0.0	0.003877	10.4	0.37	13089	5.7	0.022
A	76	3.66	1.0	0.03	0.0	0.004732	11.6	0.41	15536	6.1	0.022
A	77	3.66	1.0	0.04	0.0	0.001647	6.7	0.25	12375	2.9	0.029
A	78	3.66	1.0	0.04	0.0	0.002279	7.2	0.32	17107	4.5	0.023
A	79	3.66	1.0	0.04	0.0	0.003146	9.0	0.35	21663	4.3	0.025
A	80	3.66	1.0	0.04	0.0	0.003877	9.8	0.40	28173	5.2	0.023
A	81	3.66	1.0	0.04	0.0	0.004732	10.7	0.44	26324	5.9	0.022
A	82	3.66	1.0	0.06	0.0	0.001647	6.4	0.26	35409	2.2	0.033
A	83	3.66	1.0	0.06	0.0	0.002279	7.2	0.32	42310	3.0	0.029
A	84	3.66	1.0	0.06	0.0	0.003146	7.9	0.40	48055	4.2	0.025
A	85	3.66	1.0	0.06	0.0	0.003877	9.3	0.42	57920	4.0	0.026

Data Source	Data ID	Flume Length (*m*)	d_{50} (*mm*)	Slope (*m/m*)	Rainfall intensity (*mm/hr*)	Unit Discharge (m^2/s)	Flow Depth (m*m*)	Flow Velocity (*m/s*)	Con. (*mgl*)	Darcy-Weisbach Friction *f*	Manning Roughness n_o
A	86	3.66	1.0	0.06	0.0	0.004732	10.5	0.45	54566	4.1	0.026
A	87	3.66	1.0	0.08	0.0	0.001647	4.4	0.37	63231	5.0	0.020
A	88	3.66	1.0	0.08	0.0	0.002279	6.1	0.37	72867	3.7	0.025
A	89	3.66	1.0	0.08	0.0	0.003146	8.2	0.38	70759	2.8	0.030
A	90	3.66	1.0	0.08	0.0	0.003877	7.9	0.49	94998	4.8	0.023
A	91	3.66	1.0	0.08	0.0	0.004732	8.7	0.54	104131	5.4	0.022
A	92	3.66	1.0	0.1	0.0	0.001647	5.2	0.32	81658	2.5	0.030
A	93	3.66	1.0	0.1	0.0	0.002279	5.8	0.39	86382	3.4	0.026
A	94	3.66	1.0	0.1	0.0	0.003146	7.8	0.40	107037	2.7	0.031
A	95	3.66	1.0	0.1	0.0	0.003877	8.5	0.45	145011	3.1	0.029
A	96	3.66	1.0	0.1	0.0	0.004732	8.8	0.54	165206	4.1	0.025
B	97	1.50	0.2	0.02	0.0	0.000012	0.5	0.02	1074	0.6	0.040
B	98	1.50	0.2	0.02	0.0	0.000012	0.5	0.02	1076	0.7	0.038
B	99	1.50	0.2	0.02	0.0	0.000011	0.5	0.02	2412	0.7	0.037
B	100	1.50	0.2	0.09	0.0	0.000012	0.3	0.04	1000	0.6	0.037
B	101	1.50	0.2	0.09	0.0	0.000012	0.3	0.04	959	0.7	0.036
B	102	1.50	0.2	0.09	0.0	0.000012	0.3	0.04	1992	0.9	0.031
B	103	1.50	0.2	0.2	0.0	0.000012	0.3	0.05	966	0.5	0.040
B	104	1.50	0.2	0.2	0.0	0.000011	0.2	0.05	2318	0.6	0.036
B	105	1.50	0.2	0.02	0.0	0.000069	0.9	0.08	1232	4.0	0.017
B	106	1.50	0.2	0.02	0.0	0.000074	0.9	0.08	1189	4.8	0.016
B	107	1.50	0.2	0.09	0.0	0.000069	0.5	0.15	13382	7.3	0.012

Data Source	Data ID	Flume Length (m)	d_{50} (mm)	Slope (m/m)	Rainfall intensity (mm/hr)	Unit Discharge (m^2/s)	Flow Depth (mm)	Flow Velocity (m/s)	Con. (mgl)	Darcy-Weisbach Friction f	Manning Roughness n_o
B	108	1.50	0.2	0.09	0.0	0.000070	0.4	0.18	14145	11.8	0.009
B	109	1.50	0.2	0.2	0.0	0.000072	0.4	0.16	75035	3.9	0.016
B	110	1.50	0.2	0.2	0.0	0.000071	0.4	0.17	94640	4.3	0.015
B	111	1.50	0.2	0.02	0.0	0.000232	1.4	0.17	1345	13.6	0.010
B	112	1.50	0.2	0.02	0.0	0.000240	1.4	0.17	1146	13.4	0.010
B	113	1.50	0.2	0.09	0.0	0.000241	0.7	0.33	50207	21.1	0.007
B	114	1.50	0.2	0.09	0.0	0.000241	0.8	0.30	46473	16.1	0.009
B	115	1.50	0.2	0.2	0.0	0.000242	0.7	0.35	192975	11.5	0.010
B	116	1.50	0.2	0.2	0.0	0.000241	0.7	0.33	237344	9.4	0.011
C	117	4.88	0.5	0.057	0.5	0.000026	0.5	0.05	5512	1.3	0.027
C	118	4.88	0.5	0.057	1.0	0.000067	0.7	0.09	6701	2.5	0.021
C	119	4.88	0.5	0.057	1.5	0.000118	0.9	0.13	81224	4.0	0.018
C	120	4.88	0.5	0.057	1.9	0.000151	1.0	0.15	14569	5.3	0.015
C	121	4.88	0.4	0.1	0.5	0.000029	0.4	0.07	14903	1.3	0.027
C	122	4.88	0.4	0.1	1.0	0.000068	0.6	0.11	33227	2.7	0.020
C	123	4.88	0.4	0.1	1.5	0.000120	0.8	0.16	46229	4.3	0.016
C	124	4.88	0.4	0.1	1.9	0.000154	0.8	0.19	56891	5.4	0.015
C	125	4.88	0.4	0.15	0.5	0.000031	0.4	0.08	264401	1.6	0.024
C	126	4.88	0.4	0.15	1.0	0.000069	0.5	0.13	64394	2.7	0.020
C	127	4.88	0.4	0.15	1.5	0.000121	0.6	0.19	87798	5.1	0.015
C	128	4.88	0.3	0.15	1.9	0.000156	0.7	0.23	122589	6.5	0.013
C	129	4.88	0.3	0.2	0.5	0.000032	0.3	0.10	29558	1.8	0.022

Data Source	Data ID	Flume Length (*m*)	d_{50} (*mm*)	Slope (*m/m*)	Rainfall intensity (*mm/hr*)	Unit Discharge (m^2/s)	Flow Depth (mm)	Flow Velocity (*m/s*)	Con. (*mgl*)	Darcy-Weisbach Friction *f*	Manning Roughness n_o
C	130	4.88	0.3	0.2	1.0	0.000069	0.5	0.14	122916	2.8	0.019
C	131	4.88	0.3	0.2	1.5	0.000121	0.6	0.22	182802	5.5	0.014
C	132	4.88	0.3	0.2	1.9	0.000158	0.6	0.25	251800	6.5	0.013
C	133	4.88	0.3	0.3	0.5	0.000033	0.3	0.11	41162	1.8	0.022
C	134	4.88	0.3	0.3	1.0	0.000069	0.4	0.17	218238	3.1	0.017
C	135	4.88	0.3	0.3	1.5	0.000123	0.5	0.26	272977	5.8	0.013
C	136	4.88	0.3	0.3	1.9	0.000158	0.5	0.29	353537	6.4	0.013
C	137	4.88	0.3	0.4	0.5	0.000034	0.3	0.12	58663	1.7	0.022
C	138	4.88	0.3	0.4	1.0	0.000070	0.4	0.19	280452	3.2	0.017
C	139	4.88	0.3	0.4	1.5	0.000124	0.4	0.28	443957	5.7	0.013
C	140	4.88	0.3	0.4	1.9	0.000158	0.5	0.32	612504	6.6	0.012
B	141	1.50	0.2	0.02	0.9	0.000010	0.5	0.02	3406	0.5	0.048
B	142	1.50	0.2	0.02	0.8	0.000010	0.4	0.03	3302	1.2	0.027
B	143	1.50	0.2	0.09	0.8	0.000009	0.3	0.03	9700	0.4	0.044
B	144	1.50	0.2	0.09	0.8	0.000009	0.3	0.03	12432	0.5	0.040
B	145	1.50	0.2	0.2	0.8	0.000009	0.3	0.04	14884	0.3	0.049
B	146	1.50	0.2	0.2	0.8	0.000009	0.3	0.04	13407	0.3	0.050
B	147	1.50	0.2	0.02	2.8	0.000030	0.8	0.04	10888	1.4	0.029
B	148	1.50	0.2	0.02	2.8	0.000030	0.7	0.04	9568	1.6	0.027
B	149	1.50	0.2	0.09	2.7	0.000030	0.5	0.06	44851	1.3	0.028
B	150	1.50	0.2	0.09	2.7	0.000030	0.4	0.07	49324	1.4	0.027
B	151	1.50	0.2	0.2	2.6	0.000029	0.3	0.08	103793	1.3	0.026

Data Source	Data ID	Flume Length (m)	d_{50} (mm)	Slope (m/m)	Rainfall intensity (mm/hr)	Unit Discharge (m^2/s)	Flow Depth (mm)	Flow Velocity (m/s)	Con. (mgl)	Darcy-Weisbach Friction f	Manning Roughness n_o
B	152	1.50	0.2	0.2	2.6	0.000029	0.3	0.08	112803	1.3	0.026
B	153	1.50	0.2	0.02	3.6	0.000039	0.8	0.05	11128	1.6	0.027
B	154	1.50	0.2	0.02	3.6	0.000039	0.8	0.05	16118	1.7	0.026
B	155	1.50	0.2	0.09	3.4	0.000037	0.6	0.07	31720	1.1	0.030
B	156	1.50	0.2	0.09	3.7	0.000040	0.6	0.07	24282	1.1	0.031
B	157	1.50	0.2	0.2	3.5	0.000038	0.4	0.10	110417	1.4	0.026
B	158	1.50	0.2	0.2	3.5	0.000039	0.4	0.10	74352	1.7	0.023

* Laboratory Data Source A: Aziz and Scott (1989)
* Laboratory Data Source B: Guy and Dickinson (1990)
* Laboratory Data Source C: Kilinc (1972),

Appendix D

Hydrograph and sediment graphs of field plot experiments (Barfield et al., 1983)

Table D.1 Data of Field Experimental Runs (Barfield et al., 1983).

RUN No. 33231 (Topsoil)			RUN No. 33131 (Topsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)	Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
0.50	88.84	0.00	0.50	50.92	0.00
1.00	88.84	18.67	1.00	50.92	25.82
1.50	88.56	39.91	1.50	53.31	58.49
2.00	85.26	45.94	2.00	55.82	84.92
2.50	91.95	79.30	2.50	58.33	101.30
3.00	78.65	101.17	3.00	60.85	100.23
3.50	75.34	95.76	3.50	63.36	94.00
4.00	72.03	94.74	4.00	65.14	95.10
4.50	71.07	94.64	4.50	65.08	96.72
5.00	74.17	91.99	5.00	65.02	95.50
6.00	80.36	92.74	6.00	64.9	95.48
7.00	86.55	94.98	7.00	64.78	95.60
8.00	92.74	94.13	8.00	64.66	97.52
9.00	94.06	92.31	9.00	63.94	96.34
10.00	95.38	92.14	10.00	63.09	89.00
11.00	96.7	92.99	11.00	62.24	93.53
12.00	98.1	91.97	12.00	61.4	95.98
13.00	100.07	95.91	13.00	63.16	93.98
14.00	102.03	93.47	14.00	66.14	96.16
15.00	104	89.14	15.00	69.11	96.62
16.00	105.97	92.71	16.00	72.09	94.75
17.00	106.57	92.39	17.00	75.06	93.73
18.00	106.29	93.01	18.00	75.6	94.22
19.00	106.01	93.51	19.00	76.01	95.24
20.00	105.73	93.03	20.00	76.42	100.36
21.00	104.31	92.14	21.00	76.83	100.73
22.00	99.63	93.04	22.00	77.23	87.52
23.00	94.96	92.43	23.00	77.08	87.26
24.00	90.28	94.63	24.00	76.74	95.29
25.00	86.86	97.90	25.00	76.39	94.16
26.00	89.74	95.85	26.00	76.05	99.42
27.00	92.62	95.60	27.00	75.71	99.46
28.00	95.5	94.30	28.00	72.71	94.69

RUN No. 33231 (Topsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
29.00	98.37	93.69
30.00	89.89	88.20
30.50	80.15	67.47
31.00	70.41	37.26
31.50	60.68	18.09
32.00	50.94	8.53
32.50	41.2	4.80
33.00	36.33	3.16
33.50	36.33	1.85
34.00	36.33	0.00

RUN No. 33131 (Topsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
29.00	66.98	97.98
30.00	61.25	84.24
30.50	58.39	63.47
31.00	55.52	37.50
31.50	47.31	20.36
32.00	38.28	10.58
32.50	29.25	4.61
33.00	20.21	3.00
33.50	11.18	1.74
34.00	11.18	0.00
34.50	11.18	1.74
35.00	11.18	1.74
35.50	11.18	0.00

Table D.2 Data of Field Experimental Runs (Barfield et al., 1983).

RUN No. 32131 (Subsoil)			RUN No. 32231 (Subsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)	Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
0.50	50.64	0.00	0.50	45.89	0.00
1.00	50.64	30.52	1.00	45.89	23.18
1.50	61.71	70.16	1.50	48.15	60.15
2.00	72.78	94.04	2.00	50.93	89.59
2.50	83.85	102.12	2.50	53.7	105.87
3.00	94.92	103.71	3.00	56.47	119.13
3.50	106	92.29	3.50	59.25	124.90
4.00	112.05	98.79	4.00	62.02	107.39
4.50	116.86	104.83	4.50	64.79	92.15
5.00	121.66	105.34	5.00	66.8	85.36
6.00	131.28	102.65	6.00	69.28	95.27
7.00	140.89	99.38	7.00	71.77	104.45
8.00	139.49	104.35	8.00	74.25	106.96
9.00	130.5	104.03	9.00	76.74	100.39
10.00	121.51	103.13	10.00	78.54	84.13
11.00	114.91	102.78	11.00	75.17	97.28
12.00	123.86	114.27	12.00	71.81	97.84
13.00	132.8	104.24	13.00	68.45	97.45
14.00	140.11	89.79	14.00	65.09	96.89
15.00	136.84	99.66	15.00	67.51	95.83
16.00	133.56	104.14	16.00	70.58	99.96
17.00	135.61	106.47	17.00	73.64	99.76
18.00	143.55	103.93	18.00	76.71	100.09
19.00	151.49	102.31	19.00	78.24	105.09
20.00	153.7	103.45	20.00	78.85	100.65
21.00	151.68	105.64	21.00	79.46	96.52
22.00	149.66	103.06	22.00	80.06	106.67
23.00	147.69	101.97	23.00	82.13	99.02
24.00	145.8	104.79	24.00	86.92	90.99
25.00	143.92	104.75	25.00	91.7	100.18
26.00	142.03	108.78	26.00	96.48	97.72
27.00	141.89	105.78	27.00	101.26	98.85
28.00	141.89	102.06	28.00	97.13	100.29
29.00	141.89	107.08	29.00	92.92	103.96

RUN No. 32131 (Subsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
30.00	141.89	87.24
30.50	141.89	61.62
31.00	141.89	32.68
31.50	141.89	15.84
32.00	141.89	10.42
32.50	141.89	6.33
33.00	141.89	3.52
33.50	141.89	1.14
34.00	141.89	0.00
34.50	141.89	1.14
35.00	141.89	1.14
35.50	141.89	0.00

RUN No. 32231 (Subsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
30.00	88.72	82.03
30.50	86.62	49.99
31.00	74.57	30.17
31.50	59.77	17.86
32.00	44.97	7.48
32.50	30.17	4.44
33.00	15.37	2.67
33.50	15.37	1.15
34.00	15.37	0.00

Table D.3 Data of Field Experimental Runs (Barfield et al., 1983).

RUN No. 32331 (Subsoil)			RUN No. 31131 (Shale)		
Time (min)	**Sed. Con. (G/L)**	**Flow Rate (L/Min)**	**Time (min)**	**Sed. Con. (G/L)**	**Flow Rate (L/Min)**
0.50	28.74	0.00	1.00	18.37	0.00
1.00	28.74	23.87	1.50	18.37	15.83
1.50	32.19	57.39	2.00	18.35	33.34
2.00	36.32	85.02	2.50	18.32	52.55
2.50	40.45	96.48	3.00	18.29	74.27
3.00	44.59	95.46	3.50	18.26	88.85
3.50	48.72	97.34	4.00	18.23	97.28
4.00	52.86	101.21	4.50	18.18	105.44
4.50	55.35	98.04	5.00	18.05	105.94
5.00	57.19	97.45	6.00	17.81	101.59
5.50	59.03	99.75	7.00	17.56	101.46
6.00	60.87	100.24	8.00	17.31	102.53
7.00	64.56	99.14	9.00	16.97	102.00
8.00	68.24	97.08	10.00	16.55	100.94
9.00	70.09	98.03	11.00	16.13	102.48
10.00	70.83	100.04	12.00	15.71	102.55
11.00	71.58	99.52	13.00	15.88	100.95
12.00	72.28	96.54	14.00	16.05	100.30
13.00	72.61	99.49	15.00	16.22	98.82
14.00	72.94	102.29	16.00	16.3	98.70
15.00	73.27	100.76	17.00	16.37	101.29
16.00	73.43	100.33	18.00	16.43	103.00
17.00	73.24	99.25	19.00	16.33	100.37
18.00	73.06	99.20	20.00	16.02	99.77
19.00	72.87	99.26	21.00	15.71	101.77
20.00	75.27	98.73	22.00	15.4	101.21
21.00	80.01	104.35	23.00	15.79	100.20
22.00	84.76	100.09	24.00	16.38	100.21
23.00	89.5	95.68	25.00	16.98	99.69
24.00	84.94	100.12	26.00	17.03	100.22
25.00	75.56	100.07	27.00	15.95	100.09
26.00	66.18	100.90	28.00	14.86	100.72
27.00	56.8	100.31	29.00	13.75	101.81
28.00	55.48	99.62	30.00	12.48	90.16

RUN No. 32331 (Subsoil)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
29.00	63.67	98.30
30.00	71.87	89.57
30.50	75.97	66.26
31.00	63.65	41.44
31.50	48.04	22.25
32.00	32.44	6.58
32.50	24.64	4.75
33.00	24.64	2.95
33.50	24.64	2.13
34.00	24.64	1.38
34.50	24.64	1.38
35.00	24.64	1.38
35.50	24.64	0.00

RUN No. 31131 (Shale)		
Time (min)	Sed. Con. (G/L)	Flow Rate (L/Min)
30.50	11.84	73.11
31.00	11.21	54.80
31.50	9.49	44.16
32.00	6.95	32.13
32.50	4.41	21.64
33.00	4.24	17.12
33.50	4.24	12.73
34.00	4.24	10.59
34.50	4.24	7.50
35.00	4.24	5.22
36.00	4.24	4.60
37.00	4.24	3.70
38.00	4.24	2.84
39.00	4.24	2.43
40.00	4.24	2.04

Table D.4 Data of Field Experimental Runs (Barfield et al., 1983).

RUN No. 31231 (Shale)		
Time (min)	**Sed. Con. (G/L)**	**Flow Rate (L/Min)**
1.00	19.06	0.00
1.50	19.06	14.73
2.00	19.06	19.16
2.50	18.93	29.77
3.00	18.81	44.20
3.50	18.68	58.24
4.00	18.56	74.54
4.50	18.43	94.96
5.00	18.21	102.48
6.00	17.37	90.13
7.00	16.54	94.50
8.00	15.7	93.02
9.00	15.73	96.36
10.00	16.32	96.88
11.00	16.91	94.02
12.00	17.42	94.96
13.00	17.58	93.48
14.00	17.74	92.03
15.00	17.89	93.05
16.00	17.85	94.98
17.00	17.4	96.42
18.00	16.95	93.57
19.00	16.5	91.11
20.00	16.39	98.77
21.00	16.75	97.05
22.00	17.1	85.94
23.00	17.42	73.46
24.00	16.86	47.95
25.00	16.3	33.46
26.00	15.75	60.10
27.00	15.53	88.53
28.00	15.44	91.84
29.00	15.33	93.17
30.00	14.19	99.01

RUN No. 31231 (Shale)		
Time (min)	**Sed. Con. (G/L)**	**Flow Rate (L/Min)**
30.50	13.62	74.05
31.00	12.38	45.74
31.50	9.9	41.71
32.00	7.41	33.73
32.50	6.09	25.52
33.00	6.09	16.53
33.50	6.09	12.69
34.00	6.09	10.03
34.50	6.09	6.46
35.00	6.09	5.50
35.50	6.09	4.56
36.00	6.09	3.66
36.50	6.09	2.80
37.00	6.09	2.00
37.50	6.09	2.00
38.00	6.09	2.00
38.50	6.09	2.00
39.00	6.09	1.27
39.50	6.09	0.00

Appendix E

One dimensional diffusive wave model program code developed in this study

```
Option Explicit
'*******************************************
' Variable Announcement
'*******************************************
' Project Type Ass
Public Type Ass
 AssName As String                'Project Name
 Slope As Double                  'Bed Slope
 FlumeL As Double                 'Flume Length
 NoX As Integer                   'Number of Distance Steps
 dX As Double                     'Distance Step
 NoTime As Integer                'Number of Time Steps
 dT As Double                     'Time Step
 TotalT As Double                 'Total Simulation Time
 Roughness As Double              'Bed Roughness
 Rainfall As Double               'Rainfall Intensity
 RainDuration As Double           'Rainfall Duration
 Infiltration As Double           'Infiltration Rate
 d50 As Double                    'Mean Particle Size
 k1 As Double                     'Coefficient n1 of the Developed Soil
Erosion Equation
 k2 As Double                     'Coefficient n2 of the Developed Soil
Erosion Equation
 k3 As Double                     'Coefficient n3 of the Developed Soil
Erosion Equation
 k4 As Double                     'Coefficient n4 of the Developed Soil
Erosion Equation
 m1 As Double                     'Coefficient m1 of the Developed Soil
Erosion Equation
 m2 As Double                     'Coefficient m2 of the Developed Soil
Erosion Equation
 m3 As Double                     'Coefficient m3 of the Developed Soil
Erosion Equation
 m4 As Double                     'Coefficient m4 of the Developed Soil
Erosion Equation
 A1 As Double                     'Coefficient a of the Rainfall Enhancement
Term
 B1 As Double                     'Coefficient b of the Rainfall Enhancement
Term
 Sed_K As Double                  'Coefficient K of USLE
 Cor_K As Double                  'Coefficient K' of the Developed Soil
Erosion Equation
```

```
End Type

' Type of Calculation Point for 1-D Routing
Public Type node
 Station As Double                    ' Distance Station
 EnSlope As Double                    ' Energy Slope
 Velocity As Double                   'Flow Velocity
 PreVelocity As Double                ' Predicted Velocity of Using MacCormack
Method
 CorVelocity As Double                ' Corrected Velocity of Using MacCormack
Method
 NewVelocity As Double                ' New Velocity of Using MacCormack Method
 PreEnSlope As Double                 ' Predicted Energy Slope of Using
MacCormack Method
 CorEnSlope As Double                 ' Corrected Energy Slope of Using
MacCormack Method
 NewEnSlope As Double                 ' New Energy Slope of Using MacCormack
Method
 Depth As Double                      'Flow Depth
 PreDepth As Double                   ' Predicted Depth of Using MacCormack
Method
 CorDepth As Double                   ' Corrected Depth of Using MacCormack
Method
 NewDepth As Double                   ' New Depth of Using MacCormack Method
 Discharge As Double                  'Flow Discharge
 PreDischarge As Double               'Predicted Discharge of Using
MacCormack Method
 CorDischarge As Double               'Corrected Discharge of Using
MacCormack Method
 NewDischarge As Double               'New Discharge of Using MacCormack
Method
 Rainfall As Double                   'Rainfall
 Infiltration As Double               'Infiltration
 Fr As Double                         'Froude Number
 VS As Double                         'Unit Stream Power
 qS As Double                         'Stream Power
 hds As Double                        'Depth/Particle Size
 Cppm As Double                       'Sediment Concentration
 Sed_qs As Double                     'Sediment Transport Rate
 IV As Double                         'Rainfall Intensity / Flow Velocity
 K As Double                          'N Term in the Developed Soil Erosion
Equation
```

```
 M As Double                          'M Term in the Developed Soil Erosion
Equation
End Type

Public Point() As node                'Matrix Point as Type node
Public Project As Ass                 'Project as Type Ass
Public Ex As Integer                  'Extra Calculation Point

'******************************************
' Add A New Excel Sheet for Exporting Results
'******************************************
Public Sub OpenSheet(SheetName As String)
  Dim Book As Boolean
  Dim X As Workbook
  Dim Rtvl As Integer

  On Error Resume Next

  MsgBox ("Output data is exported into " + SheetName + "
sheet!!")

  Book = Sheets(SheetName).Select
  If Book = True Then
     Rtvl = MsgBox("A the same name worksheet is excited now.",
vbOKCancel)
     If Rtvl = 2 Then GoTo Here
     ActiveSheet.Name = SheetName
  Else
     Sheets.Add
     ActiveSheet.Name = SheetName
  End If

  Sheets(SheetName).Select
  Sheets(SheetName).Move After:=Sheets(2)
  Cells.Select
  Selection.ClearContents
  Cells(1, 1).Select

Here:
End Sub

'******************************************
```

```
' Creat the Titles for Time and Distance
'*******************************************
Public Sub TableMaker()
Dim I As Integer
Dim J As Integer

Cells(1, 1) = "Unit Discharge (cms/m)"


For I = 0 To Project.NoX
    Cells(1, I + 2) = Str(I * Project.dX) + " m"
Next I

For J = 0 To Project.NoTime
    Cells(J + 2, 1) = Str(J * Project.dT) + " sec"
Next J

End Sub

'*****************************************************
' Sediment Tranport Routing & Export Results into Excel Sheet
'*****************************************************
Public Sub TableMaker2()
Dim I As Integer
Dim J As Integer
Dim Tmpp As Double
Dim TmppI As Double

TmppI = 0
Tmpp = 0

Cells(1, 1) = "Time(sec)"
Cells(1, 2) = "Unit Discharge(cms/m)"
Cells(1, 3) = "Velocity(m/s)"
Cells(1, 4) = "Depth(m)"
Cells(1, 5) = "Energy Slope(m)"
Cells(1, 6) = "Cmgl"
Cells(1, 7) = "qs(g/s/m)"
Cells(1, 8) = "qs(g/s/m)-Julien"

Cells(1, 11) = "Fr"
Cells(1, 12) = "h/ds"
```

```
For J = 0 To Project.NoTime
    Cells(J + 2, 1) = Str(J * Project.dT)

    Cells(J + 2, 2) = Point(Project.NoX, J).Discharge
    Cells(J + 2, 3) = Point(Project.NoX, J).Velocity
    Cells(J + 2, 4) = Point(Project.NoX, J).Depth
    Cells(J + 2, 5) = Point(Project.NoX, J).EnSlope


    If Point(Project.NoX, J).Depth <= 0 Then
       Point(Project.NoX, J).Cppm = 0
       Cells(J + 2, 6) = Point(Project.NoX, J).Cppm
    Else
       Point(Project.NoX, J).Fr = Point(Project.NoX, J).Velocity
/ (9.81 * Point(Project.NoX, J).Depth) ^ 0.5
       Point(Project.NoX, J).VS = Point(Project.NoX, J).Velocity
* Point(Project.NoX, J).EnSlope
       Point(Project.NoX, J).hds = Point(Project.NoX, J).Depth /
Project.d50

       Point(Project.NoX, J).M = Project.m1 * Point(Project.NoX,
J).EnSlope + Project.m2 * Point(Project.NoX, J).Velocity +
Project.m3 * Point(Project.NoX, J).Fr + Project.m4
       Point(Project.NoX, J).K = Project.k1 * Point(Project.NoX,
J).EnSlope + Project.k2 * Point(Project.NoX, J).Velocity +
Project.k3 * Point(Project.NoX, J).Fr + Project.k4
       If J * Project.dT <= Project.RainDuration Then
           Point(Project.NoX, J).IV = Project.Rainfall / Point(
Project.NoX, J).Velocity
       Else
           Point(Project.NoX, J).IV = 0
       End If


       TmppI = 1 + 1.141 * (1 - Exp(-0.005 * (10000 * Point(
Project.NoX, J).IV) ^ 23.012))
       Tmpp = Point(Project.NoX, J).M * Point(Project.NoX, J).VS
^ Point(Project.NoX, J).K * TmppI

       Point(Project.NoX, J).Cppm = (Project.Sed_K /
Project.Cor_K) * (1922000 * (1 - Exp(-1 * Tmpp)))
```

```
       If Point(Project.NoX, J).Cppm < 0 Then Point(Project.NoX,
J).Cppm = 0

    End If
    Point(Project.NoX, J).Sed_qs = Point(Project.NoX, J).Cppm *
Point(Project.NoX, J).Discharge  'g/m :Unit
    Cells(J + 2, 6) = Point(Project.NoX, J).Cppm
    Cells(J + 2, 7) = Point(Project.NoX, J).Sed_qs
    'Julien
    Cells(J + 2, 8) = 10 ^ 6 * 23210 * Point(Project.NoX, J).
Discharge ^ 2.035 * Point(Project.NoX, J).EnSlope ^ 1.664 *
Project.Sed_K / 0.15
Next J

End Sub

'*****************************************
' Setup Initial Values for Variables
'*****************************************
Public Sub InitialCondition()
Dim I As Integer
Dim J As Integer

'Initial condition

For I = 0 To Project.NoX
  For J = 0 To Project.NoTime
    Point(I, J).Depth = 0
    Point(I, J).Discharge = 0
    Point(I, J).Velocity = 0
    Point(I, J).Slope = Project.Slope

    If (Project.dT * J) <= Project.RainDuration Then
       Point(I, J).ExRain = Project.Rainfall -
Project.Infiltration
    Else
       Point(I, J).ExRain = 0
    End If

    If Point(I, J).ExRain <= 0 Then Point(I, J).ExRain = 0
```

```
  Next J
Next I

End Sub

'******************************************
' Function of Log10
'******************************************
Public Function Log10(Number As Double)

  Log10 = Log(Number) / Log(10)


End Function


'******************************************
'  Import Input Values from Excel Sheet
'******************************************
Public Sub NewAss()

Project.AssName = Cells(4, 2)
Project.FlumeL = Cells(6, 2)
Project.Slope = Cells(7, 2)
Project.NoX = Cells(9, 2)
Project.dX = Cells(10, 2)
Project.NoTime = Cells(13, 2)
Project.dT = Cells(14, 2)
Project.TotalT = Cells(15, 2) * 60
Project.Roughness = Cells(17, 2)
Project.Rainfall = Cells(20, 2)
Project.Infiltration = Cells(26, 2)
Project.RainDuration = Cells(22, 2)

Project.k1 = Cells(4, 9)
Project.k2 = Cells(5, 9)
Project.k3 = Cells(6, 9)
Project.k4 = Cells(7, 9)
Project.m1 = Cells(11, 9)
Project.m2 = Cells(12, 9)
Project.m3 = Cells(13, 9)
Project.m4 = Cells(14, 9)
```

```
Project.A1 = Cells(17, 9)
Project.B1 = Cells(18, 9)
Project.d50 = Cells(20, 9) / 1000
Project.Sed_K = Cells(22, 9)
Project.Cor_K = Cells(25, 9)


Ex = 1 'An Extra Point

If Project.Rainfall <= Project.Infiltration Then
   MsgBox ("No Runoff!!")
   Exit Sub
End If

ReDim Point(0 To Project.NoX + Ex, 0 To Project.NoTime + 1)

Application.ScreenUpdating = False

'Creat Exported Tables
Call OpenSheet(Project.AssName + "-Hydro")
Call TableMaker
Call Hydrograph
Call ExpressTable

Call OpenSheet(Project.AssName + "-Sed")
Call TableMaker2

Application.ScreenUpdating = True

End Sub

'*******************************************
' Function of Hydrograph Simulation
' Using MacCormack Method
'*******************************************
Public Sub Hydrograph()

Dim t As Double
Dim g As Double
Dim hini As Double
Dim b As Double
Dim c As Double
```

```
Dim dtdx As Double
Dim Cc As Double
Dim CcMax As Double
Dim CcMin As Double

Dim I As Integer
Dim J As Integer

b = (1 / Project.Roughness) * Project.Slope ^ 0.5
dtdx = Project.dT / Project.dX
CcMax = -9999
CcMin = 9999


For J = 0 To Project.NoTime + 1
  For I = 0 To Project.NoX + Ex
      Point(I, J).Station = I * Project.dX
      Point(I, J).Discharge = 0
      Point(I, J).Depth = 0
      Point(I, J).Velocity = 0
      Point(I, J).EnSlope = Project.Slope
      Point(I, J).Rainfall = 0
  Next I
Next J

For J = 0 To Project.NoTime + 1
  For I = 0 To Project.NoX
      If J * Project.dT <= Project.RainDuration Then
         Point(I, J).Rainfall = (Project.Rainfall -
Project.Infiltration)
      Else
         Point(I, J).Rainfall = -Project.Infiltration
      End If
  Next I
Next J


For J = 1 To Project.NoTime

   ' Predict *********
      c = 5 / 3 * Point(I, J - 1).Velocity
      Cc = c * dtdx
```

```
      If Cc < CcMin Then CcMin = Cc
      If Cc > CcMax Then CcMax = Cc
      Knum = c * Project.dX / 2 * (1 - Cc)

      k1 = Point(I, J - 1).Velocity * Point(I, J - 1).Depth / (2
* Point(I, J - 1).EnSlope)
      Point(I, J).PreDepth = Point(I, J - 1).Depth - dtdx * c * (
Point(I + 1, J - 1).Depth - Point(I, J - 1).Depth) + dtdx2 * (k1
+ Knum) * (Point(I + 1, J - 1).Depth - 2 * Point(I, J - 1).Depth
+ Point(I - 1, J - 1).Depth) + Point(I, J - 1).Rainfall *
Project.dT

      If Point(I, J).PreDepth < 0 Then Point(I, J).PreDepth = 0
   Next I

   Point(Project.NoX + Ex, J).PreDepth = Point(Project.NoX + Ex -
 1, J).PreDepth
   Point(0, J).PreDepth = 0

   ' Predict End *********

   ' Correct *********
   For I = 1 To (Project.NoX + Ex - 1)
      If Point(I, J).PreDepth = 0 Then
         Point(I, J).PreDischarge = 0
         Point(I, J).PreVelocity = 0
         Point(I, J).PreEnSlope = Project.Slope
      Else
         Point(I, J).PreEnSlope = (Point(I, J).PreDepth - Point(I
 + 1, J).PreDepth) / Project.dX + Project.Slope
         Point(I, J).PreDischarge = (1 / Project.Roughness *
Point(I, J).PreEnSlope ^ 0.5) * Point(I, J).PreDepth ^ (5 / 3)
         Point(I, J).PreVelocity = Point(I, J).PreDischarge /
Point(I, J).PreDepth
      End If

      c = 5 / 3 * Point(I, J).PreVelocity
      Cc = c * dtdx
      If Cc < CcMin Then CcMin = Cc
      If Cc > CcMax Then CcMax = Cc
      Knum = c * Project.dX / 2 * (1 - Cc)
      k1 = Point(I, J).PreVelocity * Point(I, J).PreDepth / (2 *
```

```
Point(I, J).PreEnSlope)
      Point(I, J).CorDepth = Point(I, J).PreDepth - dtdx * c * (
Point(I, J).PreDepth - Point(I - 1, J).PreDepth) + dtdx2 * (k1 +
Knum) * (Point(I + 1, J).PreDepth - 2 * Point(I, J).PreDepth +
Point(I - 1, J).PreDepth) + Point(I, J).Rainfall * Project.dT
      If Point(I, J).CorDepth < 0 Then Point(I, J).CorDepth = 0
   Next I

   Point(Project.NoX + Ex, J).CorDepth = Point(Project.NoX + Ex -
 1, J).CorDepth
   Point(0, J).CorDepth = 0

   ' Correct End*********

  'New Value***********
   For I = 0 To (Project.NoX + Ex)
      Point(I, J).NewDepth = 0.5 * (Point(I, J).PreDepth + Point(
I, J).CorDepth)
   Next I

   For I = 0 To (Project.NoX + Ex - 1)
      Point(I, J).Depth = Point(I, J).NewDepth
      If Point(I, J).Depth = 0 Then
         Point(I, J).Discharge = 0
         Point(I, J).Velocity = 0
         Point(I, J).EnSlope = Project.Slope
      Else
         Point(I, J).EnSlope = (Point(I, J).Depth - Point(I + 1,
J).Depth) / Project.dX + Project.Slope
         Point(I, J).Discharge = (1 / Project.Roughness * Point(I
, J).EnSlope ^ 0.5) * Point(I, J).Depth ^ (5 / 3)
         Point(I, J).Velocity = Point(I, J).Discharge / Point(I,
J).Depth
      End If

   Next I
      Point(Project.NoX + Ex, J).Depth = Point(Project.NoX + Ex -
 1, J).Depth
      Point(Project.NoX + Ex, J).EnSlope = Point(Project.NoX + Ex
 - 1, J).EnSlope
      Point(Project.NoX + Ex, J).Discharge = Point(Project.NoX +
Ex - 1, J).Discharge
```

```
      Point(Project.NoX + Ex, J).Velocity = Point(Project.NoX +
Ex - 1, J).Velocity

Next J

MsgBox ("MaxCc=" + Str(CcMax) + ",  MinCc=" + Str(CcMin))

End Sub

'******************************************
' Export Hydrograph into Excel Sheet
'******************************************
Public Sub ExpressTable()
Dim I As Integer
Dim J As Integer
Dim Sum As Double
Dim RainVol As Double

For J = 0 To Project.NoTime
    For I = 0 To Project.NoX
     Cells(J + 2, I + 2) = Point(I, J).Discharge
    Next I
Next J

Sum = 0

For J = 0 To Project.NoTime
     Sum = Sum + Point(Project.NoX, J).Discharge * Project.dT
Next J

MsgBox ("Total Runoff Volume (in)=" + Str(Sum / (Project.FlumeL)
* 100 / 2.54))

End Sub
```

Appendix F

USDA experimental Watersheds W2 and W3 gauge data (Kalin, 2002)

Table F.1 Data for rainfall event 06/13/1983 of USDA Watershed W2 (Kalin, 2002).

Runoff (cfs)						Sediment			Rainfall Depth		
Time			Time			Time		concern.	Time		ST. 115
Hour	Min.	(cfs)	Hour	Min.	(cfs)	Hour	Min.	(ppm)	Hour	Min.	(in)
18	0	0.1	19	18	64.23	18	37	276	17	45	0
18	25	0.12	19	19	54.8	18	41	804	18	3	0.02
18	33	0.13	19	20	49.63	18	45	1959	18	20	0.01
18	35	0.15	19	21	44.24	18	47	5768	18	28	0.04
18	37	0.2	19	22	40.24	18	50	2835	18	33	0.03
18	41	0.27	19	23	36.47	18	53	87419	18	35	0.1
18	42	0.34	19	24	32.9	18	56	73797	18	39	0.04
18	44	0.51	19	26	26.39	19	1	95390	18	43	0.24
18	45	0.62	19	27	23.48	19	1	79493	18	49	0.04
18	46	0.95	19	29	19.1	19	2	115863	18	54	0.03
18	47	1.63	19	30	17.8	19	3	120171	18	59	0.25
18	48	1.84	19	31	16.49	19	5	122834	19	2	0.16
18	49	1.84	19	33	14.9	19	6	133793	19	3	0.11
18	50	1.74	19	37	13.36	19	8	130690	19	6	0.11
18	51	1.74	19	39	11.92	19	10	107953	19	12	0.15
18	52	2.82	19	41	10.15	19	11	95566	19	17	0.04
18	53	4.16	19	43	10.15	19	14	97777	19	19	0.01
18	54	4.16	19	45	10.57	19	16	84238	19	26	0.06
18	57	2.72	19	46	11.44	19	19	71981	19	33	0.1
18	58	2.72	19	47	11.44	19	22	67850	19	35	0.02
18	59	4.16	19	49	10.26	19	25	60996	19	50	0.02
19	0	4.51	19	50	9.31	19	27	55902	19	55	0.02
19	1	8.91	19	54	7.77	19	31	51056	20	5	0.07
19	2	16.49	19	57	6.26	19	33	48111	20	24	0.01
19	3	25.64	20	0	4.96	19	34	52445	20	32	0.02
19	4	35.55	20	5	4.04	19	37	53202	20	43	0.07
19	5	43.21	20	12	2.72	19	40	52395	20	54	0.01
19	6	54.23	20	15	2.26	19	42	44395	21	2	0.01
19	7	62.92	20	20	1.77	19	45	46826	21	13	0.01
19	8	86.85	20	25	1.41	19	50	46602	21	22	0.06
19	9	100.32	20	27	1.26	19	55	43558	21	30	0.02
19	10	103.75	20	30	1.15	20	4	31278	21	40	0.01
19	11	103.75	20	33	0.95	20	15	21572			
19	13	100.32	20	37	0.81	20	35	13759			
19	14	94.46	20	40	0.81						

Runoff (cfs)						Sediment			Rainfall Depth		
Time			Time			Time		concern.	Time		ST. 115
Hour	Min.	(cfs)	Hour	Min.	(cfs)	Hour	Min.	(ppm)	Hour	Min.	(in)
19	15	84.13	20	44	0.77						
19	16	75.19									

Table F.2 Data for rainfall event 06/13/1983 of USDA Watershed W3 (Kalin, 2002).

Runoff (cfs)						Sediment			Rainfall Depth		
Time			Time			Time		concern.	Time		ST. 112
Hour	Min.	(cfs)	Hour	Min.	(cfs)	Hour	Min.	(ppm)	Hour	Min.	(in)
18	30	0.23	19	40	16.06	18	49	1162	18	15	0
18	34	0.25	19	43	12.93	19	7	6230	18	17	0.01
18	37	0.3	19	45	11.58	19	8	9858	18	27	0.07
18	41	0.32	19	48	9.68	19	10	10141	18	31	0.04
18	43	0.34	19	50	8.68	19	12	9138	18	35	0.01
18	47	0.42	19	55	6.94	19	13	9034	18	37	0.09
18	49	0.45	20	0	5.72	19	18	16190	18	43	0.08
18	51	0.55	20	5	4.68	19	20	15515	18	46	0.11
18	55	0.6	20	8	3.75	19	20	18684	18	47	0.12
18	59	0.67	20	12	3.3	19	23	22180	18	52	0.1
19	2	0.77	20	15	2.81	19	31	17076	18	55	0.07
19	4	1	20	20	2.34	19	33	16267	18	59	0.14
19	5	1.2	20	24	2	19	35	16143	19	5	0.23
19	7	1.63	20	33	1.56	19	37	17372	19	7	0.1
19	9	2.34	20	41	1.32	19	39	12119	19	12	0.11
19	10	2.9	20	50	1.1	19	39	13115	19	20	0.09
19	11	3.52	20	58	1	19	42	12448	19	27	0.05
19	12	5.17	21	5	1	19	44	10111	19	36	0.06
19	13	7.64	21	17	0.9	19	46	8896	19	52	0.04
19	14	11.36	21	28	0.86	19	49	8081	20	6	0.06
19	15	13.44	21	37	0.81	19	51	7047	20	16	0.02
19	16	15.77	21	45	0.81	19	56	6138	20	29	0.03
19	17	22.25	21	56	0.86	20	1	5348			
19	18	26.93	22	4	0.9	20	5	4798			
19	19	30.49	22	9	0.9	20	10	4342			
19	20	32.57	22	17	0.81	20	15	3861			
19	21	36.56	22	20	0.73	20	24	3120			
19	24	36.56	22	25	0.65	20	37	2023			
19	25	35.66	22	29	0.58						
19	26	34.77	22	36	0.51						
19	28	32.98	22	43	0.45						
19	30	30.49	22	49	0.42						
19	32	26.93	23	0	0.4						
19	33	25.03	23	19	0.37						
19	35	22.25	23	39	0.34						

19	37	19.65	0	0	0.32
19	39	17.22	0	30	0.3

Appendix G

Program code of the revised CASC2D-SED

G.1 Revised CASC2D-SED Code

Note: Files with * are the original CASC2D-SED codes developed by Rojas (2002). They can be obtained from the CASC2D-SED hydrological and sediment model site (http://www.engr.colostate.edu/~pierre/ce_old/Projects/CASC2D-SED%20Web%20site%20082506/CASC2D-SED-Home.htm).

```
                              /*******************************/
                              /*          RCASC2D_DED.c      */
                              /*******************************/

#include "all.h"

            /**********************************/
            /*  GLOBAL VARIABLES DECLARATION  */
            /**********************************/

char  project_file[80],control_file[80],    rain_file[80],chn_file[80],
        header[300],elev_file[80],shap_file[80],soil_file[80],
        iman_file[80],sdep_file[80],node_file[80],link_file[80],
        summ_file[80],dis_out_file[80],sed_out_file[80],
        rname[80],write_rname[80],vinfname[80],write_vinfname[80],
        dname[80],cname[80],susname[80],erosdepname[80],
        sandfluxname[80],siltfluxname[80],clayfluxname[80],
        totalfluxname[80],sandMFACname[80],siltMFACname[80],
        clayMFACname[80],totalMFACname[80];


int     m,n,jout,kout,ncells,nman,nsoil,
        indexsdep,indexinf,indexeros,chancheck,
        nchan_link,nchan_node[100], maxlink,ichn[50][100][3],
        iter,niter,nitrn,nprn,nplt,irain,nrg,nread,
        ifcount,icount,ipcount,downstream[99],
        indexdis,ndis,**iq,unitsQ,indexsed,nsed,**ised,unitsQs,
        nodatavalue, **link,**node,**isoil, **iman, **ishp;

float   w,dt,sout,wchout,dchout,sfactorout,rmanout,sovout,
        raincount,crain,*xrg,*yrg,*areaQ, *areaQs,
        xllcorner, yllcorner,*pman, *cfactor, *pfactor, *retention,
        elconv,**e,**ret,**sdep,**vinf,**pinf,vin,vout,vinftot,
        init_ov_vol,init_ch_vol,final_ch_vol,final_ov_vol,
        chp[50][100][7],**h,**hch,*rrg,**rinty,**rtot,*qsed,**qss,
        **dqov,**dqch,qout,qoutov,qpeak,tpeak,*q,
**qovs[4],**vols[4],**ssoil[4],**SedFluxOut[4],
        **MFAC[4],**MaxFluxCout,**totnetv,**totsus, **SusC,
        tot_eroded[4],sus_ov[4],dep_ov[4],tot_ov[4],
        sus_ch[4],dep_ch[4],tot_ch[4],sed_out[4];

double amaxdepth,amindepth,amaxcdepth,amincdepth, amaxvinf,aminvinf,
        amaxnetv,aminnetv,amaxFluxCoutOv,amaxFluxCoutCh,amaxrain,
        aminrain,amaxSusCh,amaxSusOv, amaxSusCch, amaxSusCov,
ds[4],ws[4],elapsedTime;

clock_t startTime;

FILE *project_file_fptr = NULL;
FILE *shap_file_fptr = NULL;
FILE *sdep_file_fptr = NULL;
FILE *elev_file_fptr = NULL;
FILE *rain_file_fptr = NULL;
FILE *soil_file_fptr = NULL;
FILE *control_file_fptr = NULL;
FILE *chn_file_fptr = NULL;
FILE *node_file_fptr = NULL;
FILE *link_file_fptr = NULL;
```

```
FILE *Summ_file_fptr = NULL;
FILE *iman_file_fptr = NULL;
FILE *dis_out_file_fptr = NULL;
FILE *sed_out_file_fptr = NULL;
FILE *debug = NULL;


            /*********************************/
            /*   CASC2D_SED MAIN PROGRAM    */
            /*********************************/

int main(argc,argv)
    int argc;
    char *argv[];
    {
                /***********************************************/
                /*         Read and initialize data            */
                /***********************************************/

        /* Time CASC2D running
time
*/
        startTime = clock();

        /* Reads the project files
names                                                               */
        ReadProjectFile(argv[1]);

        /* Reading in the CONTROL
Information                                                      */
        ReadControlFile();

        /* Reads the input grids
headers                                                                */
        ReadGridHeaders();

        /* Dynamically allocates memory to the input & output grids
*/
        GridsMemAlloc();

        /* Reading Input
Grids
            */
        ReadInputGrids();

        /* Initializing
Variables
            */
        InitializeVars();

        /* Determines channel network topology and
variables                   */
        if(chancheck == 1)
        {
            ReadChannFile();
            ChannToplg();
        }

        /* Computing Initial Storage Volume for Overland and Channels
```

```
*/
        if(indexsdep == 1) CompInitialVol();

                /***********************************************/
                /*              Event time loop                */
                /***********************************************/

        for(iter=1;iter<=niter;iter++)
        {

            /* Updating overland and channels water
depth                                   */
            OvrlDepth( );
            if(chancheck == 1)ChannDepth();

            /* Overland and channel flow
routing                                                   */
            OvrlRout();
            if(chancheck == 1) ChannRout();

            /* Flow routing at the
outlet                                                                   */
            RoutOutlet();

            /* Sediment settling for this water depth and time
dt             */
            if (indexeros == 1) Settling();

            /* Sediment routing at the outlet, total erosion/deposition
*/
            /* volumes, sediment max./min values    and paticle
settling    */
            if (indexeros == 1)
            {
                if(qout != 0) RoutSedOut();
                SedStats();
            }

            /* Write outflow to screen and
files                                                   */
            WriteOutflow();

            /* Write output
grids
            */
            WriteGrids();

            /* Reset grids to
zero
        */
            Reset();

        } /* End of Time Loop */

                /***********************************************/
                /* Computes final volumes & writes results     */
                /***********************************************/

        /* Compute final water volumes on the overland and channels
```

```
*/
        CompFinalVol();

        /* Writing summary
file
        */
        WriteSummFlow();

        /* Compute final sed. volumes on the overland and channels
*/
        if(indexeros == 1)
        {
            SedVolumes();
            WriteSummSed();
        }

        /* Deallocate memory */
        GridsMemFree();

        /* Computes casc2d running
time                                                                    */
        RunTime(clock());

    } /* End of Main Program */


                                /*********************************/
                                /*         ChannRout.c          */
                                /*********************************/


#include "all.h"

            /***********************************/
            /*          FUNCT: ChannRout       */
            /***********************************/

extern void ChannRout()
{
    int ic,l;

    for(ic=1;ic<=maxlink;ic++)
    {
        for(l=1;l<=nchan_node[ic];l++)
        {
            /*  Note :  When ichn[ic][l+1][1] is less than
zero,               */
            /*                then that   indicates that the
channel                    */
            /*               routing for the current link is
complete.            */
            /*                There is no routing for the outlet
cell                */

            if(ichn[ic][l+1][1] > 0)
            {
             chnchn(ic,l);
            }
```

```
        } /* end For loop for the nodes in the link */
    } /* end For loop for the links  */
}

            /**********************************/
            /*          FUNCT: chnchn         */
            /**********************************/

extern void chnchn(int ic,int l)
{

    float a = 1.0;
    float vel = 0.0;
    float wch,dch,sslope,rmanch,sfactor, sf, hh,
            dq, stordep, hchan,dq_ov;
    double so, dhdx;

    int  j,k,jj,kk,jjj,iic, ijun, ill;

    /* row and column of link IC and node
l                                                  */

    j = ichn[ic][l][1];
    k = ichn[ic][l][2];

    /* row and column of following node in link
IC                                  */

    jj = ichn[ic][l+1][1];
    kk = ichn[ic][l+1][2];

    /* Note : JJJ is a check to see when the end
of                                 */
    /*        a channel link has been
reached.                                           */

    jjj = ichn[ic][l+2][1];

    /* Channel characteristics
:
*/

    wch = chp[ic][l][2];            /*
width                               */
    dch = chp[ic][l][3];            /*
depth                               */
    sslope = chp[ic][l][4];     /* side slope                    */
    rmanch = chp[ic][l][5];     /* manning's n                 */
    sfactor = chp[ic][l][6];    /* sinuosity factor        */
    stordep = sdep[j][k];           /* Storage depth             */
    hchan = hch[j][k];              /* Channel water depth  */
    hh = hch[j][k] - stordep;

    /*if(fabs(hh) < 1e-4) hh=0.0;    check for negligible water depth */

    /* Channel
slope
                            */
    if (j != jj && k != kk)
```

```
    {
       so = (double)((e[j][k] - e[jj][kk])/(1.4142*w*sfactor));
       dhdx = (double)((hch[jj][kk] - hch[j][k])/(1.4142*w*sfactor));
    }
    else
    {
       so = (e[j][k] - e[jj][kk])/(w*sfactor);
       dhdx = (hch[jj][kk] - hch[j][k])/(w*sfactor);
    }

    dq_ov = 0.0;

    /* If jjj<0, then the end of the channel link has been reached. */
    /* Slope is computed with last node of current link and first
*/
    /*  node of following
one
            */

    if(jjj < 0)
    {
        for (iic=1;iic<=maxlink;iic++)
        {
            if(jj == ichn[iic][1][1] && kk == ichn[iic][1][2])
            {
                if (j != jj && k != kk)
                {
                  so = (double)((e[j][k] - dch - e[jj][kk] +
chp[iic][1][3])/(1.4142*w*sfactor));
                  dhdx = (double)((hch[jj][kk] -
hch[j][k])/(1.4142*w*sfactor));
                }
                else
                {
                  so = (e[j][k] - dch - e[jj][kk] +
chp[iic][1][3])/(w*sfactor);
                  dhdx = (hch[jj][kk] -
hch[j][k])/(w*sfactor);
                }
                ijun = iic;
            }
        }
    }

    sf = (float)(so - dhdx + 1e-30);

    /* Nota de Jorge: Sf se deberia quedar con el mismo signo */
    if(fabs(sf) < 1e-20) sf = (float)(1e-20);

    if (sf < 0.0)
    {
        a = (float)(-1.0*a);

        if (jjj < 0)
        {
            /* Take channel chars. of the 1st node of downstream link */

            wch = chp[ijun][1][2];
            dch = chp[ijun][1][3];
```

```
            sslope = chp[ijun][1][4];
            rmanch = chp[ijun][1][5];
            sfactor = chp[ijun][1][6];
        }
        else
        {
            /*Take channel chars. of the next node within current link
*/

            wch = chp[ic][l+1][2];
            dch = chp[ic][l+1][3];
            sslope = chp[ic][l+1][4];
            rmanch = chp[ic][l+1][5];
            sfactor = chp[ic][l+1][6];
        }

        stordep = sdep[jj][kk];
        hchan = hch[jj][kk];
        hh = hch[jj][kk] - stordep;

        /*if(fabs(hh) < 1e-4) hh = 0.0;check for negligible  depth
*/
    }

    /* Determining
discharge
                    */

    dq = chnDischarge(hchan,hh,wch,dch,stordep,rmanch,a,sf,sfactor);

    /* Transfer flow from cell (j,k) to
(jj,kk)                                         */

    dqch[j][k] = dqch[j][k] - dq;
    dqch[jj][kk] = dqch[jj][kk] + dq;

    /* If (j,k) is a printout flow discharge internal location
*/

    for (ill=1;ill<=ndis;ill++)
    {
        if(j == iq[ill][1] && k == iq[ill][2]) q[ill] = dq;
    }

    /* Channel sediment
routing
        */

    if(indexeros == 1 && dq != 0.0 && hchan !=0)
    {
        if(a >= 0.0)
        {
            RoutSedChn(dq,sf,j,k,jj,kk,wch,hchan);
        }
        else
        {
            RoutSedChn(-dq,-sf,jj,kk,j,k,wch,hchan);
        }
    }
```

```
}       /* End of CHNCHN */


                              /********************************/
                              /*          ChannToplg.c        */
                              /********************************/


#include "all.h"

extern void ChannToplg()
{

    int maxchn = 1;
    int
upstream1[50],upstream2[50],upstream3[50],upstream4[50],upstream5[50],ups
tream6[50], upstream7[50],
            ic,l,rr,cc,ll,rc,i,j,k, p,q,ro,co,outlink,outnode;
    float elev;

    outlink = link[jout][kout];
    outnode = node[jout][kout];
    /* Determining Row and Column
Locations                                                        */

    for(j=1;j<=m;j++)
    {
        for(k=1;k<=n;k++)
        {
            if(link[j][k] !=0 && node[j][k] !=0)
            {
                ichn[link[j][k]][node[j][k]][1] = j;
                ichn[link[j][k]][node[j][k]][2] = k;

                if(maxchn < node[j][k]) maxchn = node[j][k];
            }
        }
    }

    /* NOTE: because the last node of one link and the first node
*/
    /* of the downstream link is the same, the number of nodes of
*/
    /* one link is the last numbered node in the link plus one
*/
    maxchn = maxchn + 2;  /* Maximum number of nodes +
1                     */

    /* Determining Downstream and Upstream
Linkages                                         */
    for(i=1;i<=maxlink;i++)
    {
        /*downstream[i] = 0;  */
        upstream1[i] = 0;
        upstream2[i] = 0;
        upstream3[i] = 0;
        upstream4[i] = 0;
```

```
        upstream5[i] = 0;
        upstream6[i] = 0;
        upstream7[i] = 0;
    }

    for(i=1;i<=maxlink;i++)
    {
        rr = ichn[i][1][1];
        cc = ichn[i][1][2];

        /* Checking
North
                                */

        if(rr-1 >= 1)
        {
          if(e[rr][cc] <= e[rr-1][cc])
          {
            ll = link[rr-1][cc];

            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;

}

                else
                {
                    upstream7[i] = ll;
                }
        /*      downstream[ll] = i;         */
            }
          }
        }

        /* Checking
South
```

```
                    */

        if(rr+1 <= m)
        {
            ll = link[rr+1][cc];
          if(e[rr][cc] <= e[rr+1][cc])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;

}

                else
                {
                    upstream7[i] = ll;
                }
        /*      downstream[ll] = i;          */
            }
          }
        }

        /* Checking
West
                    */

        if(cc-1 >= 1)
        {
            ll = link[rr][cc-1];
          if(e[rr][cc] <= e[rr][cc-1])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
```

```
                    else if(upstream2[i] == 0)
                    {
                        upstream2[i] = ll;
                    }
                    else if(upstream3[i] == 0)
                    {
                        upstream3[i] = ll;
                    }
                    else if(upstream4[i] == 0)
                    {
                        upstream4[i] = ll;
                    }
                    else if(upstream5[i] == 0)
                    {
                        upstream5[i] = ll;
                    }
                    else if(upstream6[i] == 0)
                    {
                        upstream6[i] = ll;

}

                    else
                    {
                        upstream7[i] = ll;
                    }
        /*          downstream[ll] = i;          */
                }
            }
        }

        /* Checking
East
                          */

        if(cc+1 <= n)
        {
            ll = link[rr][cc+1];
          if(e[rr][cc] <= e[rr][cc+1])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
```

```
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;

}

                else
                {
                    upstream7[i] = ll;
                }
        /*      downstream[ll] = i;          */
            }
          }
        }


        /* Checking North East
-----
                        */

        if(cc+1 <= n && rr-1 >= 1)
        {
            ll = link[rr-1][cc+1];
          if(e[rr][cc] <= e[rr-1][cc+1])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;

}

                else
                {
                    upstream7[i] = ll;
```

```
                }
        /*      downstream[ll] = i;           */
            }
          }
        }

        /* Checking South East
-----
                        */

        if(cc+1 <= n && rr+1 <= m)
        {
            ll = link[rr+1][cc+1];
          if(e[rr][cc] <= e[rr+1][cc+1])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;
}
                else
                {
                    upstream7[i] = ll;
                }
            /*  downstream[ll] = i;           */
            }
          }
        }

        /* Checking North West
-----
                        */

        if(cc-1 >= 1 && rr-1 >= 1)
        {
            ll = link[rr-1][cc-1];
```

```
          if(e[rr][cc] <= e[rr-1][cc-1])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;

}

                else
                {
                    upstream7[i] = ll;
                }
            /*  downstream[ll] = i;    */
            }
          }
        }

        /* Checking South West
------
                    */

        if(cc-1 >= 1 && rr+1 <= m)
        {
            ll = link[rr+1][cc-1];
          if(e[rr][cc] <= e[rr+1][cc-1])
          {
            if(ll !=0 && ll != i)
            {
                if(upstream1[i] == 0)
                {
                    upstream1[i] = ll;
                }
                else if(upstream2[i] == 0)
                {
                    upstream2[i] = ll;
                }
                else if(upstream3[i] == 0)
```

```
                {
                    upstream3[i] = ll;
                }
                else if(upstream4[i] == 0)
                {
                    upstream4[i] = ll;
                }
                else if(upstream5[i] == 0)
                {
                    upstream5[i] = ll;
                }
                else if(upstream6[i] == 0)
                {
                    upstream6[i] = ll;

}

                else
                {
                    upstream7[i] = ll;
                }
            /*  downstream[ll] = i;   */
            }
          }
        }

    }

    /*Adding the downstream Row and Column to the end of every Link */

    for(i=1;i<=maxlink;i++)
    {
        rc = 0;

        for(j=1;j<=maxchn;j++)
        {
            if(i != outlink)
            {
                if(ichn[i][j][1] == 0 && rc == 0)
                {
                    if(ichn[i][j-1][1] > 0)
                    {
                        ll = downstream[i];

                        ichn[i][j][1] = ichn[ll][1][1];
                        ichn[i][j][2] = ichn[ll][1][2];
                    }
                    rc = 1;
                }
            }
        }
    }

    /* Adding a -1 to the end of every link except for the outlet
*/
    /*
link
                                                    */
```

```
    for(i=1;i<=maxlink;i++)
    {
        for(k=1;k<=2;k++)
        {
            for(j=1;j<=maxchn;j++)
            {
                if(i != outlink)
                {
                    if(ichn[i][j][k] == 0)
                    {
                        if(ichn[i][j-1][k] > 0) ichn[i][j][k] = -1;
                    }
                }
            }
        }
    }

    /* Writing channel network info and topology to summary file
*/

    printf("Number of Channels         = %ld \n",maxlink);
    printf("Maximum Length of Channels = %ld \n",maxchn);

    fprintf(Summ_file_fptr,"\nChannel Linkage Information\n");
    fprintf(Summ_file_fptr,"---------------------------\n\n");

    fprintf(Summ_file_fptr,"Maximum Number of Links = %ld \n",

                            maxlink);
    fprintf(Summ_file_fptr,"Maximum Number of Nodes = %ld \n\n",

                             maxchn);

    for(i=1;i<=maxlink;i++)
    {
        for(k=1;k<=2;k++)
        {
            for(j=1;j<=maxchn;j++)
            {
                if(j<maxchn)
                {
                    fprintf(Summ_file_fptr,"%5ld",ichn[i][j][k]);
                }
                else
                {
                    fprintf(Summ_file_fptr,"%5ld \n",ichn[i][j][k]);
                }
            }
        }

        fprintf(Summ_file_fptr,"\n");
    }

    fprintf(Summ_file_fptr,
                        " Link    Downstream    Upstream1    Upstream2
Upstream3    Upstream4    Upstream5    Upstream6    Upstream7 \n\n");

    for(i=1;i<=maxlink;i++)
    {
```

```
        fprintf(Summ_file_fptr,"%4ld %10ld  %10ld  %10ld  %10ld  %10ld
%10ld  %10ld  %10ld \n",

i,downstream[i],upstream1[i],upstream2[i],upstream3[i],upstream4[i],upstr
eam5[i],upstream6[i],upstream7[i]);

        printf("%4ld %10ld  %10ld  %10ld  %10ld  %10ld  %10ld  %10ld
%10ld \n",

i,downstream[i],upstream1[i],upstream2[i],upstream3[i],upstream4[i],upstr
eam5[i],upstream6[i],upstream7[i]);
    }

    /* Mask grid value equal to 2 if channel going through
it              */
    for(ic=1;ic<=maxlink;ic++)
    {
        for(l=1;l<=maxchn;l++)
        {
            j=ichn[ic][l][1];
            k=ichn[ic][l][2];

            if(j > 0 && chancheck == 1)
            {
             ishp[j][k] = 2;
            }
        }
    }


    /* Channel characteristics at the
outlet                                                          */
    wchout = chp[outlink][outnode][2];
    dchout = chp[outlink][outnode][3];
    rmanout = chp[outlink][outnode][5];
    sfactorout = chp[outlink][outnode][6];
    for(p=-1; p<=1; p++)
    {
        for(q=-1; q<=1; q++)
        {
            ro = jout + p;
            co = kout + q;
            if(ro>0 && ro<=m && co>0 && co<=n && ro!=jout && co!=kout)
                if(ishp[ro][co] == 2 ) elev = e[ro][co];
        }
    }
    sout = (float)(fabs(elev - e[jout][kout] )/ w);


}


                        /********************************/
                        /*          Fcts_sed.c          */
                        /********************************/

#include "all.h"
```

```
/************************************/
/*           FUNCT: EHcap          */
/************************************/


/* Determines the sediment transport capacity based on the
*/
/* Engelund and Hansen transport equation. Result is in m3
*/

extern float EHcap(int SizeFr,float width,float depth, float sf,float
discharge)
{
    float Cw[4], Rh,V, EHcapacity;

    /* Hydraulic radius                                            */
    Rh = (width*depth)/(width + 2 * depth);

    /* Flow velocity                                               */
    V = (float)(discharge/(width*depth));

    /* Concentration by weight by size fraction                    */
    Cw[SizeFr] = (float)(0.05*(G/(G-1)) *
                         fabs(V*sf)/sqrt((G-1)*g*ds[SizeFr]) *
                         sqrt(Rh*fabs(sf)/((G-1)*ds[SizeFr]) ) ) ;

    /* Engelund and Hansen transport capacity  (in m3)             */
    EHcapacity = (float)(discharge * Cw[SizeFr] / 2.65)*dt ;

    return(EHcapacity);

}
            /************************************/
            /*          FUNCT: ShihCap          */
            /************************************/


/* Determines the sediment transport capacity based on the
*/
/* Shih and Yang transport equation. Result is in m3          */

extern float ShihCap(float discharge,float width, float sf, int jfrom,
int kfrom)
{
    float SedCapacity, UnitDischarge,FrNo, Velocity, VS, Cmgl_Shih, Mp,
Np, iV, EnI,TmpP;

    UnitDischarge = (float)(fabs(discharge/width));
    Velocity=(float)(UnitDischarge/h[jfrom][kfrom]);
    FrNo=(float)(Velocity/sqrt(g*h[jfrom][kfrom]));
    VS=(float)(fabs(Velocity*sf));
    iV=(float)(rinty[jfrom][kfrom]/Velocity);

    Mp=(float)(-0.654*fabs(sf)-3.848*Velocity+0.227*FrNo+2.657);
    Np=(float)(-1.629*fabs(sf)-1.17*Velocity+0.071*FrNo+1.532);
    EnI=(float)(1+1.141*(1-exp(-0.005*pow((10000*iV),23.012))));
    TmpP=(float)(-1*Mp*pow(VS,Np)*EnI);
```

```
    Cmgl_Shih=(float)(1922000*(1-exp(TmpP)));

    /*Pusle = pfactor[iman[jfrom][kfrom]];*/

    SedCapacity = (float)(Cmgl_Shih * UnitDischarge/0.1/2.65*0.000001 *
width * dt);

    return(SedCapacity);

}

            /************************************/
            /*         FUNCT: TransferSed       */
            /************************************/

/* Transfers a certain volume of sediment, VolToTransfer, from      */
/* an outgoing cell (jfrom,kfrom) to receiving cell (jto,kto).The */
/* source, can be the suspended,deposited or parent material in     */
/* outgoing cell.  The transferred volume of sed. will be added     */
/* in all cases onto the suspended portion of the receiving cell. */
/* If the outgoing cell is the outlet cell, the VolToTransfer is    */
/* not added into a receiving cell but to the variable that holds */
/* the total volume of sediment leaving the basin by size fraction*/

extern void TransferSed(int SizeFr,float **Source[],
                                                float VolToTransfer,
                                                int jfrom,int kfrom,int
jto,int kto)
{
    /* For each size fraction, substracts the sediment volume that  */
  /* has been transported from the suspended, deposited or parent */
    /* material of the outgoing cell                                */
    Source[SizeFr][jfrom][kfrom] -= VolToTransfer;


    if(jfrom==jout && kfrom==kout)
    {
        /* If outgoing cell is the outlet cell, keeps track by size    */
        /* fraction of the volume of sediment that left the basin      */
        sed_out[SizeFr] += VolToTransfer;
    }
    else
    {
        /* if outgoing cell is not the outlet cell, it adds by size    */
        /* fraction the transported sediment to the suspended portion */
        /* of the receiving cell                                        */
        qovs[SizeFr][jto][kto] += VolToTransfer;
    }
}

            /************************************/
            /*         FUNCT: FindMFAC          */
            /************************************/

/* For each time step, finds the maximum flux-averaged concentr.  */
/* leaving the outgoing cell for the total volume of sediment     */
/* (** MaxFluxCout) or by size fraction (** MFAC[SizeFr])         */

extern void findMFAC(int jfrom,int kfrom,float totQSout, float
```

```
discharge,float qs[4])
{
    int SizeFr;

    if(MaxFluxCout[jfrom][kfrom] < totQSout/dt/fabs(discharge)
                &&   fabs(discharge) > 1E-4)
    {
      /* For the total volume of sediment leaving the outgoing cell */
        MaxFluxCout[jfrom][kfrom] =(float)(totQSout/dt/fabs(discharge));

        /* By size fraction                                              */
        for (SizeFr = 1; SizeFr <=3; SizeFr++)
        {
            MFAC[SizeFr][jfrom][kfrom]
=(float)(qs[SizeFr]/dt/fabs(discharge));
        }
    }
}


                        /******************************/
                        /*      InitializeVars.c      */
                        /******************************/


#include "all.h"

extern void InitializeVars()
{
    int SizeFr,i,j,k;

    /* Grid
values
                                    */
    for(j=1;j<=m;j++)
    {
        for(k=1;k<=n;k++)
        {
            if(ishp[j][k] != nodatavalue)
            {
                /* retention depth was entered in
mm.                                         */
                ret[j][k] = retention[iman[j][k]] / 1000;
                dqov[j][k] = 0.0;
                dqch[j][k] = 0.0;
                vinf[j][k] = 0.0;
                rtot[j][k] = 0.0;
                MaxFluxCout[j][k] = 0.0;
                qss[j][k] = 0.0;
                rinty[j][k] = 0.0;

                for (SizeFr=1;SizeFr<=3;SizeFr++)
                {
                    vols[SizeFr][j][k] = 0.0;
                    ssoil[SizeFr][j][k] = 0.0;
                    qovs[SizeFr][j][k] = 0.0;
                    SedFluxOut[SizeFr][j][k] = 0.0;
                    MFAC[SizeFr][j][k] = 0.0;
                }
```

```
            }
        }
    }

    for(i=1;i<=99;i++)
    {
        downstream[i]=0;
    }

    /* Total
volumes
                                                    */
    vin = 0.0;
    vout = 0.0;
    vinftot = 0.0;

    /*
Counters
                                                            */
    raincount = 0;
    icount = 1;
  ipcount = 1;
  ifcount = 1;

    /* Variables that hold min. and max.
values                                                             */
    amaxdepth = 9e-30;
    amindepth = 9e30;
    amaxcdepth = 9e-30;
    amincdepth = 9e30;
    amaxvinf = 9e-30;
    aminvinf = 9e30;
    amaxnetv = 9e-30;
    aminnetv = 9e30;
    amaxFluxCoutOv = 9e-30;
    amaxFluxCoutCh = 9e-30;
    amaxrain = 9e-30;
    aminrain = 9e30;
    amaxSusOv = 9e-30;
    amaxSusCh = 9e-30;
    amaxSusCov = 9e-30;
    amaxSusCch = 9e-30;

    /* Sediment volumes by size fraction
(sand/silt/clay)                                         */
    for (SizeFr=1;SizeFr<=3;SizeFr++)
    {
        tot_eroded[SizeFr] = 0.0;    /* Eroded   during the
simulation          */
        sus_ov[SizeFr] = 0.0;        /* Suspended remaining on
overl.          */
        dep_ov[SizeFr] = 0.0;        /* Deposited remaining on
overl.          */
        tot_ov[SizeFr] = 0.0;        /* Susp.+ Dep. remaining on
overl.    */
        sus_ch[SizeFr] = 0.0;        /* Suspended remaining in
channels     */
        dep_ch[SizeFr] = 0.0;        /* Deposited remaining in
channels     */
```

```
        tot_ch[SizeFr] = 0.0;        /* Susp.+ Dep. remaining in
channels    */
        sed_out[SizeFr] = 0.0;
    }

    /* Water volumes at the beggining & end of the  simulation
*/
    init_ov_vol = 0.0;
    init_ch_vol = 0.0;
    final_ov_vol = 0.0;
    final_ch_vol = 0.0;

    /* Sediment characts. for medium grain sizes at 20 degrees C
*/
    ds[1] = 0.00035;                    /* Sand median diameter [m]
0.00035 */
    ds[2] = 0.000016 ;              /* Silt median diameter [m]
0.000016*/
    ds[3] = 0.000001;                   /* Clay median diameter [m]
0.000001*/
    ws[1] = 0.036;                      /* Sand fall veleocity (m/s)
0.036       */
    ws[2] = 2.2e-4;                     /* Silt fall velocity
(m/s)       2.2e-4  */
    ws[3] = 8.6e-7;                     /* Clay fall velocity
(m/s)       8.6e-7  */

    /* Initializing ICHN Array.  NOTE: it is assumed that the max.  */
    /* number of nodes at any link is
100                                                             */
    for(i=1;i<=maxlink;i++)
        for(k=1;k<=2;k++)
            for(j=1;j<=99;j++)
                ichn[i][j][k] = 0;

    /* Initializing channel and overland water
depths                                      */
    for(j=1;j<=m;j++)
    {
        for(k=1;k<=n;k++)
        {
            hch[j][k] = 0.0;

            if(indexsdep == 1)
            {
                h[j][k] = sdep[j][k];

                if(sdep[j][k] > 0.0 && chancheck == 1 && link[j][k] > 0)
                {
                    hch[j][k] = sdep[j][k];

                    if(sdep[j][k] > chp[link[j][k]][node[j][k]][3])
                    {
                        h[j][k] = sdep[j][k] -
chp[link[j][k]][node[j][k]][3];
                    }
                    else
                    {
                        h[j][k] = 0.0;
```

```
                    }
                }
            }
            else
            {
                h[j][k] = 0.0;
                sdep[j][k] = 0.0;
            }
        }
    }
}


                        /********************************/
                        /*          MemAlloc.c          */
                        /********************************/


#include "all.h"

extern void GridsMemAlloc()
{
    int SizeFr;

    printf("starting memmory allocation");
    /* Allocate memory for input
matrices                                                        */
    ishp = intMemAlloc2d(m,n);
    isoil = intMemAlloc2d(m,n);
    iman  = intMemAlloc2d(m,n);
    e = floatMemAlloc2d(m,n);
    ret = floatMemAlloc2d(m,n);

    if(chancheck == 1)
    {
        link = intMemAlloc2d(m,n);
        node = intMemAlloc2d(m,n);
    }

    sdep = floatMemAlloc2d(m,n);

    /* Allocate memory for output
matrices                                                   */

    if(indexinf == 1)   vinf = floatMemAlloc2d(m,n);

    h = floatMemAlloc2d(m,n);
    hch = floatMemAlloc2d(m,n);

    if(indexeros == 1)
    {
        qss = floatMemAlloc2d(m,n);
        MaxFluxCout = floatMemAlloc2d(m,n);
        totsus = floatMemAlloc2d(m,n);
        SusC = floatMemAlloc2d(m,n);
        totnetv = floatMemAlloc2d(m,n);

        /* Allocate memory for 3-D
matrices                                                        */
```

```
        for (SizeFr=0;SizeFr<4;SizeFr++)
        {
            qovs[SizeFr] = floatMemAlloc2d(m,n);
            vols[SizeFr] = floatMemAlloc2d(m,n);
            ssoil[SizeFr] = floatMemAlloc2d(m,n);
            SedFluxOut[SizeFr] = floatMemAlloc2d(m,n);
            MFAC[SizeFr] = floatMemAlloc2d(m,n);
        }
    }

    dqov = floatMemAlloc2d(m,n);
    dqch = floatMemAlloc2d(m,n);
    rtot = floatMemAlloc2d(m,n);
    rinty = floatMemAlloc2d(m,n);

    printf("memory allocation ends");
}
            /***********************************/
            /*          intMemAlloc2d          */
            /***********************************/

/* Allocates memory for a integer 2D-grid of NoRows*NoCols */
int** intMemAlloc2d(int NoRows, int NoCols)
{
    int k;
    int** matrix2d;

    matrix2d = (int **)malloc((NoRows+1)*sizeof(int *));

    for(k=0; k<(NoRows+1); k++)
    {
        *(matrix2d + k) =(int*)malloc((NoCols+1)*sizeof(int));
    }

    return matrix2d;
}

            /***********************************/
            /*         floatMemAlloc2d         */
            /***********************************/

/* Allocates memory for a floating 2D-grid of NoRows*NoCols */
float** floatMemAlloc2d(int NoRows, int NoCols)
{
    int k;
    float** matrix2d;

    matrix2d = (float **)malloc((NoRows+1)*sizeof(float *));

    for(k=0; k<(NoRows+1); k++)
    {
        *(matrix2d + k) =(float*)malloc((NoCols+1)*sizeof(float));
    }

    return matrix2d;
}
```

```
                    /*******************************/
                    /*      ReadControlFile.c      */
                    /*******************************/


#include "all.h"


extern void ReadControlFile()
{
    int i,j,l;

    printf("Reading CONTROL file \n");

    fprintf(Summ_file_fptr,"\nCONTROL Input Data \n");
    fprintf(Summ_file_fptr,  "================== \n");
    fprintf(Summ_file_fptr,  "Control file : %s\n", control_file);

    fscanf(control_file_fptr,"%f %ld %ld %ld %ld",
                &dt,&niter,&nitrn,&nprn,&nplt);

    fprintf(Summ_file_fptr,
    "DT = %2.2f sec NITER= %ld NITRN = %ld NPRN = %ld NPLT = %ld\n\n",

dt,niter,nitrn,nprn,nplt);

    fprintf(Summ_file_fptr,"Overland outlet cell: \n");
    fscanf(control_file_fptr,"%ld %ld %f",&jout,&kout,&sovout);
    fprintf(Summ_file_fptr,"JOUT = %ld KOUT = %ld SOVOUT = %g \n\n",

                        jout,kout,sovout);

    fscanf(control_file_fptr,"%i",&chancheck);
    fprintf(Summ_file_fptr,"CHANCHECK= %i \n",chancheck);

    fscanf(control_file_fptr,"%f",&elconv);
    fprintf(Summ_file_fptr,"ELCONV = %.2f\n",elconv);

    fprintf(Summ_file_fptr,"\nRainfall Data \n");
    fprintf(Summ_file_fptr,  "============= \n");

    fscanf(control_file_fptr,"%ld ",&irain);
    fprintf(Summ_file_fptr,"IRAIN = %ld \n",irain);

    if(irain == 0)
    {
     fscanf(control_file_fptr,"%f ",&crain);
     fprintf(Summ_file_fptr,"CRAIN = %.3f (mm/h)\n",crain);
    }
    else
    {
     fprintf(Summ_file_fptr,"Rainfall file: %s \n",rain_file);
     fscanf(control_file_fptr,"%ld %ld ",&nrg,&nread);
     fprintf(Summ_file_fptr,"NRG = %ld NREAD = %ld \n",nrg,nread);

     xrg = (float*) malloc((nrg+1)*sizeof(float));
     yrg = (float*) malloc((nrg+1)*sizeof(float));
```

```
     rrg = (float*) malloc((nrg+1)*sizeof(float));

     for(l=1;l<=nrg;l++)
     {
         fscanf(control_file_fptr,"%f %f ",&xrg[l],&yrg[l]);
         fprintf(Summ_file_fptr,"XRG[%ld] = %8.6f\tYRG[%ld] = %8.6f \n",

                l,xrg[l],l,yrg[l]);
     }
    }

    fprintf(Summ_file_fptr,"\nLand Use Parameters \n");
    fprintf(Summ_file_fptr,  "=================== \n");

    /* Allocate memory for the variables derived from the landuse
*/
    pman = (float*) malloc((nman+1)*sizeof(float));
    retention = (float*) malloc((nman+1)*sizeof(float));
    cfactor = (float*) malloc((nman+1)*sizeof(float));
    pfactor = (float*) malloc((nman+1)*sizeof(float));

    fscanf(control_file_fptr," %ld %ld ",&nman,&indexsdep);
    fprintf(Summ_file_fptr,"NMAN = %ld INDEXSDEP = %ld \n\n",
nman,indexsdep);
    fprintf(Summ_file_fptr,"\tIndex\tManning
Intercept.\tCusle\tPusle\n");
    fprintf(Summ_file_fptr,"\t-----\t-- n --    -- [mm]
--\t-----\t-----\n");

    for(i=1;i<=nman;i++)
    {
     fscanf(control_file_fptr,"%f %f %f %f",
                   &pman[i], &retention[i],&cfactor[i],&pfactor[i]);
     fprintf(Summ_file_fptr,
            "\t%3ld%11.3f\t%10.3f\t%5.3f\t%5.3f\n",
                           i,pman[i],retention[i],cfactor[i],pfactor[i]);
    }

    fprintf(Summ_file_fptr,"\nSoil type Parameters \n");
    fprintf(Summ_file_fptr,  "==================== \n");

    fscanf(control_file_fptr,"%i %i %i",&indexinf,&indexeros,&nsoil);
    fprintf(Summ_file_fptr,"INDEXINF= %i INDEXEROS= %i NSOIL= %i \n",

        indexinf,indexeros,nsoil);

    fprintf(Summ_file_fptr,
        "\n        Index    Ks        G          Md        %%Sand
%%Silt     %%Clay     Kusle\n");
    fprintf(Summ_file_fptr,
        "        -----  [cm/h]    [cm]       -----     -----
-----    -----     -----\n");
    if(indexinf == 1)
    {
     pinf = floatMemAlloc2d(nsoil,8);

     /* Read values from the CONTROL file */
     for(i=1;i<=nsoil;i++)
     {
```

```
         fprintf(Summ_file_fptr,"%10i",i);
         for(j=1;j<=7;j++)
         {
             fscanf(control_file_fptr,"%g ",&pinf[i][j]);
             fprintf(Summ_file_fptr,"%10.3f",pinf[i][j]);
             /* Converts Ks: cm/h ->
m/s                                                                   */
             if(j ==1) pinf[i][j] = pinf[i][j]/3600/100;
             /* Converts G:  cm ->
m
*/
             if(j ==2) pinf[i][j] = pinf[i][j]/100;
         }

         fprintf(Summ_file_fptr,"\n");
     }
    }

    fprintf(Summ_file_fptr,"\nInternal Gages Data \n");
    fprintf(Summ_file_fptr,  "------------------- \n");

    fscanf(control_file_fptr,"%ld %ld %i",&indexdis,&ndis, &unitsQ);
    fprintf(Summ_file_fptr,
                             "INDEXDIS = %ld  NDIS = %ld  Q_units = %i \n",

indexdis,ndis, unitsQ);

    if(indexdis == 1)
    {
      fprintf(Summ_file_fptr,"\n        Gage      Row      Column
Area\n");
        fprintf(Summ_file_fptr,"        ----      ---      ------
[has]\n");
        iq = intMemAlloc2d(ndis,2);
        areaQ = (float*) malloc((ndis+1)*sizeof(float));

        for (i=1;i<=ndis;i++)
        {
         fprintf(Summ_file_fptr,"       %2i",i);
         for (j=1;j<=2;j++)
         {
             fscanf(control_file_fptr,"%ld ",&iq[i][j]);
             fprintf(Summ_file_fptr,"%10i",iq[i][j]);
         }
         fscanf(control_file_fptr,"%f", &areaQ[i]);
         fprintf(Summ_file_fptr,"%14.3f\n", areaQ[i]);
        }
    }


    fprintf(Summ_file_fptr,"\nInternal Sediment Gages Data \n");
    fprintf(Summ_file_fptr,  "---------------------------- \n");

    fscanf(control_file_fptr,"%ld %ld %i",&indexsed,&nsed, &unitsQs);
    fprintf(Summ_file_fptr,
                                       "INDEXSED = %ld  NSED = %ld
Qs_Units = %i\n",

          indexsed,nsed, unitsQs);
```

```
    if(indexsed == 1)
    {
        fprintf(Summ_file_fptr,"\n        Gage      Row
Column      Area\n");
        fprintf(Summ_file_fptr,"        ----      ---      ------
[has]\n");
        ised = intMemAlloc2d(nsed,2);
        areaQs = (float*) malloc((nsed+1)*sizeof(float));

        for(i=1;i<=nsed;i++)
        {
         fprintf(Summ_file_fptr,"       %2i",i);
         for (j=1;j<=2;j++)
         {
             fscanf(control_file_fptr,"%ld ",&ised[i][j]);
             fprintf(Summ_file_fptr,"%10i",ised[i][j]);
         }
         fscanf(control_file_fptr,"%f", &areaQs[i]);
         fprintf(Summ_file_fptr,"%14.3f\n",areaQs[i]);
        }
    }

    printf("Successfully Read All CONTROL Information \n");
    fclose(control_file_fptr);

    /* Allocate memory for the vector that holds the
flow                       */
    /* dicharge and sediment discharge at each of those locations
*/
    q =  (float*) malloc((ndis+1)*sizeof(float));
    qsed = (float*) malloc((nsed+1)*sizeof(float));

}


                        /********************************/
                        /*         RoutSedChn.c         */
                        /********************************/


#include "all.h"

            /**********************************/
            /*        FUNCT: RoutSedChn       */
            /**********************************/

extern void RoutSedChn(float dq,float sf,int jfrom,int kfrom,
                                             int jto,int kto,float
wch,float hchan)
{
    int SizeFr;
    float TotQs,V,supply,qs[4],adv_factor,
                EHvol[4],SUSvol[4], XSScap[4], BMvol[4];

    /* Total sediment volume out of outgoing cell is initialized   */
    TotQs = 0.0;

    /* Flow velocity (m/s)                                         */
```

```
    V = (float)(dq/(wch*hchan));

    for (SizeFr=1; SizeFr<=3;SizeFr++)
    {
      /* Sediment supply in the outgoing cell if found in suspension*/
        /* (**qovs) and/or in deposition (**vols)                      */
      supply = qovs[SizeFr][jfrom][kfrom] + vols[SizeFr][jfrom][kfrom];

        /* initialize qs to 0 in case that supply = 0    */
        qs[SizeFr] = 0;

        /* If there is sediment supply in the outgoing cell              */
        if (supply != 0)
        {
            /* Transport capacity [m3] for size fraction SizeFr using
*/
            /* the Engelund and Hansen equation
*/
            EHvol[SizeFr] = EHcap(SizeFr,wch,hchan,sf,dq);

            /* Suspended sediment transport capacity [m3] by advection
*/
            /* Limit this transport by
availability                                              */

            adv_factor = (float)(MIN(V*dt/w,1));

            SUSvol[SizeFr] = qovs[SizeFr][jfrom][kfrom] * adv_factor;

            /* Transfers the volume SUSvol[SizeFr] of sediment size
*/
            /* fraction, SizeFr in suspension in the outgoing cell
*/
            /* to the suspended portion of the receiving cell
*/

            TransferSed(SizeFr,qovs,SUSvol[SizeFr],jfrom,kfrom,jto,kto);

            /* Excess capacity [m3] to move seds. from the bed-material
*/

            XSScap[SizeFr] = (float)(MAX(0, EHvol[SizeFr] -
SUSvol[SizeFr]));

            /* Bed-material transport capacity [m3] by
advection              */

            BMvol[SizeFr] = vols[SizeFr][jfrom][kfrom] * adv_factor;

            /* Volume of bed-material transported   out of
(jfrom,kfrom)    */

            BMvol[SizeFr] = (float)(MIN(XSScap[SizeFr],BMvol[SizeFr]));

            /* Transfers the volume BMvol[SizeFr] of sediment size
*/
            /* fraction, SizeFr in deposition in the outgoing cell
*/
```

```
            /* to the suspended portion of the receiving cell
*/

            TransferSed(SizeFr,vols,BMvol[SizeFr],jfrom,kfrom,jto,kto);


            /* Total volume of transported sediment from outgoing cell
*/

            qs[SizeFr] = SUSvol[SizeFr] + BMvol[SizeFr];

            /* Updates total sediment volume leaving the outgoing cell
*/

            qss[jfrom][kfrom] += qs[SizeFr];
            /*if (qss[jfrom][kfrom]<9e-28) qss[jfrom][kfrom]=0;  */

            /* Keeps track of sediment flux out of the outgoing cell
*/

            SedFluxOut[SizeFr][jfrom][kfrom] += qs[SizeFr] / dt;

            /* Total sediment volume leaving the outgoing
cell            */

            TotQs += qs[SizeFr];
        }
    }

    /* Calls the function findMFAC to find the maximum flux         */
    /* averaged concentration out of the outgoing cell              */
    findMFAC(jfrom,kfrom,TotQs,dq,qs);

}


                        /********************************/
                        /*        RoutSedOvrl.c         */
                        /********************************/


#include "all.h"

extern void RoutSedOvrl(float dqq, float sf,int jfrom,int kfrom, int
jto,int kto)
{
    float V, qsSUS[4],qsADV[4],qsSUStot,SUStot, DEPtot,qsBM[4],
                totXSScap,capacity[4],RESIDcap, qsBMtot,
                qsEROS[4],qsEROStot,percent[4],qs[4],qsShih,Kusle;

    int SizeFr,SoilType;

    /* SizeFr: Soil size fraction:    1: sand; 2: silt; 3: clay     */
    /* Outgoing cell : (jfrom, kfrom)                               */
    /* Receiving cell: (jto, kto)                                   */

    /* Flow velocity [m/s]                                          */
    V = (float)(fabs(dqq)/(w * h[jfrom][kfrom]));
```

```
    /* Initialize sediment volumes to zero                              */
    qsSUStot = 0;       /* Total transported suspended volume           */
    qsBMtot = 0;        /* Total transported bed material volume        */
    qsEROStot = 0;      /* Total transported eroded material volume     */
    SUStot = 0;         /* Total susp. volume in outgoing cell          */
    DEPtot = 0;         /* Total deposited volume in outgoing cell      */

    /* Finds soil type for the outgoing overland cell                   */
    SoilType = isoil[jfrom][kfrom];
    Kusle = pinf[SoilType][7];

    /* Transport Capacity using the Shih & Yang's equation          */
    qsShih = ShihCap(dqq,w,sf,jfrom,kfrom);

    /* Initialize transport volumes by size fraction to zero            */
    for(SizeFr=1;SizeFr<=3;SizeFr++)
    {                      /* For size fraction SizeFr:                 */
        qsSUS[SizeFr] = 0;  /* transported volume from suspension        */
        qsBM[SizeFr] = 0 ;  /* transported volume from deposition        */
        qsEROS[SizeFr] = 0; /* transported volume from parent material*/
        qs[SizeFr] = 0;     /* total transported volume                  */
        /* Outgoing cell total suspended and deposited sediment          */
        SUStot += qovs[SizeFr][jfrom][kfrom];
        DEPtot += vols[SizeFr][jfrom][kfrom];

    }

    for(SizeFr=1;SizeFr<=3;SizeFr++) /* For each size fraction          */
    {
        /* Is this size fraction present in suspended portion ?          */
        if(qovs[SizeFr][jfrom][kfrom] > 0)
        {
            if(qsShih < SUStot) /* Transport capacity is < total
suspended*/
            {
                /* Volume that can be transported using the KR
equation   */
                capacity[SizeFr] = qsShih *
qovs[SizeFr][jfrom][kfrom]/SUStot;
                /* Volume that can be transported by advective
processes  */
                qsADV[SizeFr] = qovs[SizeFr][jfrom][kfrom] * V * dt / w;
                /* Transport the maximum between the last two
quantities  */
                qsSUS[SizeFr] =
(float)(MAX(capacity[SizeFr],qsADV[SizeFr]));
            }
            else /* If transport capacity is > total suspended sediment
*/
            {
                /* Transport all the suspended sediment for this size
fr. */
                qsSUS[SizeFr] = qovs[SizeFr][jfrom][kfrom];
            }

            /* Transfers the volume qsSUS[SizeFr] of sediment size
*/
            /* fraction, SizeFr, in suspension in the outgoing cell
*/
```

```
            /* to the suspended portion of the receiving cell
*/
            TransferSed(SizeFr,qovs,qsSUS[SizeFr],jfrom,kfrom,jto,kto);

            /* Keeps track of the total volume of sediment coming from
*/
            /* the suspended material portion of the outgoing cell
*/
            qsSUStot += qsSUS[SizeFr];
        }
    }

    /* Reduces the transport capacity by the volume that has already*/
    /* been transported from the outgoing cell to get the total     */
    /* excess capacity                                              */
    totXSScap = (float)(MAX(0,qsShih - qsSUStot));

    /* If there is an excess transport capacity, and provided that  */
    /* the outgoing cell has previously deposited material, we use  */
    /* this capacity to put this sediment in suspension and move it */
    /* to the suspended portion of the receiving cell               */
    if(totXSScap > 0 && DEPtot > 0)
    {
        for(SizeFr=1;SizeFr<=3;SizeFr++)
        {
        /* Is this size fraction present in deposited portion ?        */
            if(vols[SizeFr][jfrom][kfrom] > 0)
            {
                /* Excess transport capacity is < total deposited
sediment*/
                if(totXSScap < DEPtot)
                {

                    /* Volume that can be transported for this
size          */
                    /* fraction is proportional to its percentage in
the     */
                    /* total deposited
sediment                          */
                    qsBM[SizeFr] = totXSScap *
vols[SizeFr][jfrom][kfrom] / DEPtot;
                }
                else /* If transport capacity is > total deposited
sed.    */
                {
                    /* Transport all the deposited sed. for this size
fr.    */
                    qsBM[SizeFr] = vols[SizeFr][jfrom][kfrom];
                }

            /* Transfers the volume qsBM[SizeFr] of sediment size
*/
            /* fraction, SizeFr, in deposition in the outgoing cell
*/
            /* to the suspended portion of the receiving cell
*/

TransferSed(SizeFr,vols,qsBM[SizeFr],jfrom,kfrom,jto,kto);
```

```
            /* Keeps track of the total volume of sediment leaving
*/
            /* the deposited material portion of the outgoing cell
*/
          qsBMtot += qsBM[SizeFr];
            }
        }
    }

    /* Reduces the excess transport capacity by the total volume    */
    /* of sediment, qsBMtot,that has alrady been transported        */
    /* from the deposited portion of the outgoing cell              */
    RESIDcap = (float)(MAX(0,(totXSScap * Kusle)- qsBMtot));

    /* Any residual transport capacity is used to erode the parent  */
    /* material.  Erosion by size fraction is proportional to its   */
    /* percentage in the parent material                            */
    if(RESIDcap >0)
    {
        for(SizeFr=1;SizeFr<=3;SizeFr++)
        {
            /* Percentage of fraction, SizeFr, in the parent material
*/
            percent[SizeFr] = pinf[SoilType][SizeFr + 3];

            /* Volume of eroded parent material corresponding to size
*/
            /* fraction SizeFr
*/
            qsEROS[SizeFr] = RESIDcap * percent[SizeFr];

            /* Keeps track of the total volume of sediment coming from
*/
            /* the parent material portion of the outgoing cell
*/
            qsEROStot += qsEROS[SizeFr];

            /* Transfers the volume qsEROS[SizeFr] of sediment size
*/
            /* fraction, SizeFr from the outgoing cell parent material
*/
            /* to the suspended portion of the receiving cell
*/
            TransferSed(SizeFr,ssoil,qsEROS[SizeFr],jfrom,kfrom,jto,kto);
        }
    }

    /* Keeps track of the total sediment volume leaving the         */
    /* outgoing cell (coming from all 3 sources)                    */
    qss[jfrom][kfrom] += qsSUStot + qsBMtot + qsEROStot;

    for(SizeFr=1;SizeFr<=3;SizeFr++)
    {
        /* Total sediment volume leaving the outgoing cell by size    */
        /* fraction                                                   */
        qs[SizeFr] = qsSUS[SizeFr] + qsBM[SizeFr] + qsEROS[SizeFr];

        /* Keeps track of the sediment flux [m3/s] by size fraction   */
        /* out of the outgoing cell                                   */
```

```
        SedFluxOut[SizeFr][jfrom][kfrom] += qs[SizeFr] / dt;
    }

    /* Calls the function findMFAC to find the maximum flux         */
    /* averaged concentration out of the outgoing cell              */
    findMFAC(jfrom,kfrom,qsShih,dqq,qs);

}

                        /*******************************/
                        /*          SedStats.c         */
                        /*******************************/


#include "all.h"

extern void SedStats()
{
    int j,k, SizeFr;
    float totdepv,totscourv;

    for(j = 1;j <= m; j++)
    {
        for(k = 1;k <= n; k++)
        {
            if(ishp[j][k] != nodatavalue)
            {
                totdepv = 0.0;
                totscourv = 0.0;
                totsus[j][k] = 0.0;

                for(SizeFr=1;SizeFr<=3;SizeFr++)
                {
                    /* Total (sand+silt+clay) deposited sed. volume
(m3)        */

                    totdepv += vols[SizeFr][j][k];

                    /* Total (sand+silt+clay) scoured sed. volume
(m3)          */

                    totscourv += ssoil[SizeFr][j][k];

                    /* Total (sand+silt+clay) suspended sed. volume
(m3)        */

                    totsus[j][k] += qovs[SizeFr][j][k];
                }

                /* Net (deposited - eroded) sediment volume
(mm)                  */

                totnetv[j][k] = (totdepv + totscourv) * 1000 / (w*w);

                /* Min. and Max. net erosion/depostion volume
(m3)              */

                aminnetv = MIN((double)(totnetv[j][k]) , aminnetv);
                amaxnetv = MAX(totnetv[j][k] , amaxnetv);
```

```
                /* Absolute max. flux conc., susp. volume and
suspended     */
                /* conc. at any time step and at any overland
cell            */

                if(ishp[j][k] == 1)
                {
                    amaxFluxCoutOv =
MAX(MaxFluxCout[j][k],amaxFluxCoutOv);
                    amaxSusOv = MAX(totsus[j][k],amaxSusOv);

                    /* Limiting the mim. water depth to 0.5mm will
reduce        */
                    /* very high concentration
calculations                             */

                    if(h[j][k] > 5E-4)
                    {
                        SusC[j][k] = totsus[j][k] / (h[j][k]*w*w);
                        amaxSusCov = MAX(amaxSusCov,SusC[j][k]);
                    }
                    else
                    {
                        SusC[j][k] = 0;
                    }
                }

                /* Absolute max. flux conc., susp. volume and
suspended     */
                /* conc. at any time step and at any channel
cell            */

                if(ishp[j][k] == 2)
                {

                    amaxFluxCoutCh =
MAX(amaxFluxCoutCh,MaxFluxCout[j][k]);
                    amaxSusCh = MAX(amaxSusCh,totsus[j][k]);

                    if(hch[j][k] > 5E-4)
                    {
                        SusC[j][k] = totsus[j][k] /

(hch[j][k]*w*chp[link[j][k]][node[j][k]][2]);

                        amaxSusCch = MAX(amaxSusCch,SusC[j][k]);
                    }
                    else
                    {
                        SusC[j][k] = 0;
                    }
                }
            }
        }
    }
}
```

```
                              /*******************************/
                              /*       ReadChannFile.c       */
                              /*******************************/


#include "all.h"

extern void ReadChannFile()
{
    char ch;
    int j,k;

    printf("Reading Channel Data \n");

    do{
     ch=fscanf(chn_file_fptr,"%ld",&nchan_link);
     ch=fscanf(chn_file_fptr,"%ld",&nchan_node[nchan_link]);
     ch=fscanf(chn_file_fptr,"%ld",&downstream[nchan_link]);
    /* fprintf(Summ_file_fptr,"Link = %ld Downstream = %ld \n\n",
nchan_link,downstream[nchan_link]);  */

     for(k=1;k<=nchan_node[nchan_link];k++)
     {
         for(j=1;j<=6;j++)
         {
             ch=fscanf(chn_file_fptr,"%f ",&chp[nchan_link][k][j]);
         }
     }

    } while(ch!=EOF);

    maxlink = nchan_link;

    /* Writing Channel Information to Output Summary
File                        */

/*  fprintf(Summ_file_fptr,"\n Channel Input Data \n");
    fprintf(Summ_file_fptr," ------------------ \n");
    for(i=1;i<=maxlink;i++)
    {
        for(k=1;k<=nchan_node[i];k++)
        {
            for(j=1;j<=6;j++)
            {
                fprintf(Summ_file_fptr,"CHP[%ld][%ld][%ld] = %f ",

    i,k,j,chp[i][k][j]);
            }
            fprintf(Summ_file_fptr,"\n");
        }
    }
*/

    printf("Successfully Read Channel Data \n");
    fclose(chn_file_fptr);

}
```

Appendix H

Case studies of the Goodwin Creek Watershed, and Watersheds W2 and W3

```
#############  INPUT DATA FILES  #############
CONTROL                     Input/run2.dat
PRECIP                      Input/30minAver.pre
CHANNEL                     input/chann0.035.dat

#############  INPUT DATA GRIDS  #############
ELEVATION                   Input/DEM30mod.asc
SOIL                        Input/soils30.asc
LANDUSE                     Input/luse30.asc
MASK                        Input/mask.asc
LINK                        Input/links.asc
NODE                        Input/nodes.asc

##############  OUTPUT FILES  ################
SUMMARY                     Output/run2.sum
DISCHARGE_OUT               Output/run2.q
SEDIMENT_OUT                Output/run2.qs

######  OUTPUT TIME SERIES GRID NAMES  #######
RAINFALL                    hydromaps/rain
INF_DEPTH                   hydromaps/infvol
WATER_DEPTH                 hydromaps/depth
SED_CONC                    hydromaps/conc
EROS_DEP                    sedMaps/netvol
SAND_FLUX_OUT               sedmaps/fluxSAND
SILT_FLUX_OUT               sedmaps/fluxSILT
CLAY_FLUX_OUT               sedmaps/fluxCLAY
TOTAL_FLUX_OUT              sedmaps/fluxTOT
```

```
 0.5  84000  36000  120  120
 170  1  0.003368
 1
 1

 1
 16            3600
 231568.7117   3791553.7426
 233072.7721   3793603.9817
 236856.3335   3794839.5058
 236459.33     3795732.9309
 236662.9499   3793699.8824
 238396.5605   3794734.2989
 239756.4195   3795151.8743
 234644.3966   3793655.021
 237777.6768   3796476.9739
 238787.2374   3796056.2956
 233758.5726   3794401.0867
 235620.4058   3795906.558
 234840.6096   3792778.0814
 233122.6924   3791785.0733
 236523.6428   3792701.0902
 238663.3566   3793326.2882

 4  0
 0.25          1.5            0.0005         1
 0.01          0              0              1
 0.1           0.8            0.05           1
 0.2           1              0.02           1

 1  1  7
 0.35          22             0.33           0.25           0.55
0.2           0.4
 0.32          14             0.33           0.25           0.55
0.2           0.1
 0.37          17             0.33           0.3            0.6
0.1           0.2
 0.38          22             0.33           0.25           0.55
0.2           0.4
 0.36          18             0.33           0.3            0.6
0.1           0.2
 0.45          22             0.33           0.3            0.6
0.1           0.1
 0.4           15             0.33           0.25           0.55
0.2           0.1

 1  6  3
 170           1              2062.165
 81            125            357.822
 32            162            111.491
 100           169            162.979
 40            233            137.561
 100           104            165.062

 1  6  2
 170           1              2062.165
 81            125            357.822
 32            162            111.491
```

100	169	162.979
40	233	137.561
100	104	165.062

```
0.090625    0.202857143 0.162758621 0.105   0.201081081 0.201081081
0.128   0.201025641 0.102941176 0.22    0.163030303 0.201666667 0.3815
0.24    0.165555556 0.401081081
0.09375 0.171428571 0.061241379 0.032058824 0.016216216 0.016216216
0.079027027 0.015384615 0.105058824 0.292   0.104969697 0.518333333
0.015   0   0.033333333 0.016216216
0.151988636 0.674285714 1.156   1.110941176 0.277702703 1.082702703
1.221861862 0.523589744 1.236210526 1.08    0.927   1.085454545 0.4635
0.303636364 0.395656566 0.537702703
1.39030303  1.329206349 1.269473684 1.282   1.511153846 1.48
1.336111111 1.423333333 1.199122807 1.2296  1.205   0.858545455 1.355
1.576363636 1.390454545 1.425
1.706666667 2.032222222 1.921954887 1.93    1.653846154 1.623076923
0.9125  1.87    1.783333333 1.384114286 1.943636364 1.728380952
1.790454545 1.71375 1.529736842 1.724444444
1.116666667 0.699090909 0.575238095 0.355714286 1.424   0.706153846
1.238970588 0.858095238 0.546666667 0.829047619 0.59969697  0.682619048
0.976480938 0.89125 0.922596491 0.560818713
0.608181818 0.514909091 0.683333333 0.984285714 0.616   0.572991453
0.399529412 0.492571429 0.430666667 0.488095238 0.518666667 0.169285714
0.478064516 0.515   0.402666667 0.394736842
0.269644269 0.144   0.21    0.2 0.236   0.457777778 0.546307692
0.248121212 0.576   0.417142857 0.276888889 0.280714286 0.266363636
0.24    0.32    0.328181818
0.052173913 0.032   0.06    0.009473684 0.044   0.0425  0.029358974
0.034878788 0.04    0   0.048479532 0.195   0.040695187 0.0512  0.04
0.051818182
0   0   0   0.010526316 0   0.0175  0.008333333 0.013   0   0
0.012631579 0.06    0.012941176 0.0088  0   0
```

```
1  41
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
2          25        3.5        0         0.035        1
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2	30	4.4	0	0.035	1
2	30	4.4	0	0.035	1
2	30	4.4	0	0.035	1
2	30	4.4	0	0.035	1
2	30	4.4	0	0.035	1
2	30	4.4	0	0.035	1
2	30	4.4	0	0.035	1
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11	60				
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2	27	4.3	0	0.035	1
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2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1
2	27	4.3	0	0.035	1

```
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
2        27      4.3     0       0.035     1
12  39
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
2        30      4.5     0       0.035     1
```

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2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
2	30	4.5	0	0.035	1
13 45					
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
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2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1

2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
2	30	4.7	0	0.035	1
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2	30	4.7	0	0.035	1
14	38				
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2	20	3	0	0.035	1
2	20	3	0	0.035	1
2	20	3	0	0.035	1
2	20	3	0	0.035	1
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2	20	3	0	0.035	1
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2	20	3	0	0.035	1
2	20	3	0	0.035	1
2	20	3	0	0.035	1
2	20	3	0	0.035	1
2	20	3	0	0.035	1
2	20	3	0	0.035	1
15	38				
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2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1
2	22	3.5	0	0.035	1

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2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
2   22   3.5   0   0.035   1
16  46
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
2   50   5     0   0.035   1
```

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2	50	5	0	0.035	1
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2	50	5	0	0.035	1
17	50				
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2	48	5	0	0.035	1
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2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1

2	48	5	0	0.035	1
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2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1
2	48	5	0	0.035	1
18	41				
2	34	6.05	0	0.035	1
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2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
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2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
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2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1
2	34	6.05	0	0.035	1

```
CONTROL Input Data
==================
Control file : Input/run2.dat
DT = 0.50 sec NITER= 84000 NITRN = 36000 NPRN = 120 NPLT = 120

Overland outlet cell:
JOUT = 170 KOUT = 1 SOVOUT = 0.003368

CHANCHECK= 1
ELCONV = 1.00

Rainfall Data
=============
IRAIN = 1
Rainfall file: Input/30minAver.pre
NRG = 16 NREAD = 3600
XRG[1] = 231568.718750  YRG[1] = 3791553.750000
XRG[2] = 233072.765625  YRG[2] = 3793604.000000
XRG[3] = 236856.328125  YRG[3] = 3794839.500000
XRG[4] = 236459.328125  YRG[4] = 3795733.000000
XRG[5] = 236662.953125  YRG[5] = 3793700.000000
XRG[6] = 238396.562500  YRG[6] = 3794734.250000
XRG[7] = 239756.421875  YRG[7] = 3795151.750000
XRG[8] = 234644.390625  YRG[8] = 3793655.000000
XRG[9] = 237777.671875  YRG[9] = 3796477.000000
XRG[10] = 238787.234375 YRG[10] = 3796056.250000
XRG[11] = 233758.578125 YRG[11] = 3794401.000000
XRG[12] = 235620.406250 YRG[12] = 3795906.500000
XRG[13] = 234840.609375 YRG[13] = 3792778.000000
XRG[14] = 233122.687500 YRG[14] = 3791785.000000
XRG[15] = 236523.640625 YRG[15] = 3792701.000000
XRG[16] = 238663.359375 YRG[16] = 3793326.250000

Land Use Parameters
===================
NMAN = 4 INDEXSDEP = 0

    Index   Manning    Intercept.   Cusle   Pusle
    -----   -- n --    -- [mm] --   -----   -----
      1      0.250       1.500  0.001    1.000
      2      0.010       0.000  0.000    1.000
      3      0.100       0.800  0.050    1.000
      4      0.200       1.000  0.020    1.000

Soil type Parameters
====================
INDEXINF= 1 INDEXEROS= 1 NSOIL= 7

        Index    Ks        G          Md         %Sand       %Silt
%Clay     Kusle
        -----  [cm/h]    [cm]        -----      -----       -----
-----     -----
          1     0.350    22.000      0.330      0.250       0.550
0.200      0.400
          2     0.320    14.000      0.330      0.250       0.550
0.200      0.100
          3     0.370    17.000      0.330      0.300       0.600
```

```
0.100      0.200
           4     0.380    22.000     0.330     0.250     0.550
0.200      0.400
           5     0.360    18.000     0.330     0.300     0.600
0.100      0.200
           6     0.450    22.000     0.330     0.300     0.600
0.100      0.100
           7     0.400    15.000     0.330     0.250     0.550
0.200      0.100

Internal Gages Data
-------------------
INDEXDIS = 1  NDIS = 6  Q_units = 3

        Gage      Row      Column      Area
        ----      ---      ------      [has]
         1        170         1      2062.165
         2         81       125       357.822
         3         32       162       111.491
         4        100       169       162.979
         5         40       233       137.561
         6        100       104       165.062

Internal Sediment Gages Data
----------------------------
INDEXSED = 1  NSED = 6 Qs_Units = 2

        Gage      Row      Column      Area
        ----      ---      ------      [has]
         1        170         1      2062.165
         2         81       125       357.822
         3         32       162       111.491
         4        100       169       162.979
         5         40       233       137.561
         6        100       104       165.062

ASCII grid files header
-------------------------
ncols        281
nrows        172
xllcorner    231614.00
yllcorner    3791509.00
cellsize     30.00
NODATA_value     -9999

The following Grids have been read:
 --------------------------------
Elevation Grid: Input/DEM30mod.asc
Shape Grid:     Input/mask.asc
Soils Grid:     Input/soils30.asc
Landuse Grid:   Input/luse30.asc
Node Grid:  Input/nodes.asc
Link Grid:  Input/links.asc

Number of cells in basin: 22942
Basin area: 2064.780 [ha]

Channel Linkage Information
```

```
--------------------------

Maximum Number of Links = 18
Maximum Number of Nodes = 77

  136  135  135  134  134  133  132  131  131  130  130  130  129  129
128  128  128  128  127  127  126  126  126  125  125  125  125  125
125  125  124  124  123  123  122  122  121  121  120  120  120   -1
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
   64   64   63   63   62   62   62   62   61   61   60   59   59
58   58   57   56   55   55   54   54   53   52   52   51   50   49
48   47   46   46   45   45   44   44   43   43   42   42   41   40
-1    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0

  126  126  126  126  126  126  125  125  124  124  123  123  122  121
121  120  119  118  118  117  116  116  115  114  113  113  112   -1
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
  126  125  124  123  122  121  121  120  120  119  119  118  118  118
117  117  117  117  116  116  116  115  115  115  115  114  114   -1
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0

  112  111  111  110  109  109  108  108  107  107  106  106  105  105
104  103  103  102  102  101  101  100  100   99   99   98   98   98
97   97   96   95   -1    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
  114  114  113  113  113  112  112  111  111  110  110  109  109  108
108  108  107  107  106  106  105  105  104  104  103  103  102  101
101  100  100  100   -1    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0

   96   97   97   97   97   98   98   98   98   99   99  100  100  100
100  100  100  100  101  101  102  102  103  103  104  104  105  105
106  106  106  106  106  106  106  106  106  106  106  106  106  107
107  107  108  108  108  108  108  108  108  109  109  109  109  109
109  109  108  108  108  107  107  106  106  105  105  104   -1    0
0    0    0    0    0    0    0
  219  219  218  217  216  216  215  214  213  213  212  212  211  210
209  208  207  206  206  205  205  204  204  203  203  202  202  201
201  200  199  198  197  196  195  194  193  192  191  190  189  189
188  187  187  186  185  184  183  182  181  181  180  179  178  177
176  175  175  174  173  173  172  172  171  171  170  170   -1    0
0    0    0    0    0    0    0

  104  103  103  102  101  100   99   99   98   98   97   96   96
```

```
95   94   93   93   92   92   91   91   90   90   90   89   89   89
89   88   88   88   88   88   87   87   87   86   86   86   86   86
86   86   85   85   85   85   85   85   85   85   85   85   85   85
85   85   85   84   84   84   83   83   82   82   82   82   81   81
81   80   80   79   79   78   78   -1
  170  170  169  169  169  169  169  168  168  167  167  167  166  166
166  166  165  165  164  164  163  163  162  161  161  160  159  158
158  157  156  155  154  154  153  152  152  151  150  149  148  147
146  146  145  144  143  142  141  140  139  138  137  136  135  134
133  132  132  131  130  130  129  129  128  127  126  126  125  124
124  123  123  122  122  121   -1

   32   32   32   33   33   33   33   33   33   33   32   32   32
31   31   31   30   30   31   31   31   32   32   32   32   32   32
32   32   32   32   33   33   34   34   35   35   36   36   36   37
37   38   38   39   39   40   41   41   42   43   43   44   45   46
47   48   49   -1    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0
  185  184  183  183  182  181  180  179  178  177  177  176  175  175
174  173  173  172  172  171  170  170  169  168  167  166  165  164
163  162  161  161  160  160  159  159  158  158  157  156  156  155
155  154  154  153  153  153  152  152  152  151  151  151  151  151
151  151   -1    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0

   48   47   47   47   46   46   46   45   45   45   45   44   44
44   43   43   42   42   42   42   41   41   41   41   41   41   41
41   41   40   40   40   40   40   40   41   41   41   41   41   41
41   41   41   41   40   40   40   41   41   41   41   41   41   -1
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0
  255  255  254  253  253  252  251  251  250  249  248  248  247  246
246  245  245  244  243  242  242  241  240  239  238  237  236  235
234  234  233  232  231  230  229  229  228  227  226  225  224  223
222  221  220  220  219  218  218  217  216  215  214  213   -1    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0

   41   41   41   41   42   42   43   43   44   44   44   45   45
45   46   46   47   47   48   48   49   50   50   51   51   52   53
53   54   54   55   55   56   56   57   58   58   59   59   60   60
61   61   62   62   63   63   63   -1    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0
  213  212  211  210  210  209  209  208  208  207  206  206  205  204
204  203  203  202  202  201  201  201  200  200  199  199  199  198
198  197  197  196  196  195  195  195  194  194  193  193  192  192
191  191  190  190  189  188   -1    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0

   67   67   67   68   68   68   69   69   69   69   69   69   70
70   71   71   71   71   70   70   69   69   68   68   67   67   66
66   65   65   64   64   63   -1    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0
  208  207  206  206  205  204  204  203  202  201  200  199  199  198
```

198 197 196 195 195 194 194 193 193 192 192 191 191 190
190 189 189 188 188 -1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

63 63 63 63 63 63 63 63 63 63 63 63 63
63 62 62 62 61 61 60 60 59 59 58 58 58 57
57 57 56 56 55 55 54 54 53 53 52 52 51 51
50 50 50 49 49 49 49 49 49 49 49 -1 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
188 187 186 185 184 183 182 181 180 179 178 177 176 175
175 174 173 173 172 172 171 171 170 170 169 168 168 167
166 166 165 165 164 164 163 163 162 162 161 161 160 160
159 158 158 157 156 155 154 153 152 151 -1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

49 49 49 49 49 49 49 49 50 50 51 51 52
52 53 53 53 53 54 55 55 56 57 58 58 59 59
60 60 61 61 62 63 63 64 65 66 67 67 68 68
69 69 70 70 71 71 72 73 73 74 74 75 75 76
76 77 77 77 78 -1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
151 150 149 148 147 146 145 144 144 143 143 142 142 141
141 140 139 138 138 138 137 137 137 137 136 136 135 135
134 134 133 133 133 132 132 132 132 132 131 131 130 130
129 129 128 128 127 127 127 126 126 125 125 124 124 123
123 122 121 121 -1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

78 78 79 79 80 80 81 81 82 82 83 83 84
84 85 85 86 87 88 88 89 89 89 89 89 90 90
91 91 92 92 93 93 93 94 94 95 95 95 -1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
121 120 120 119 119 118 118 117 117 116 116 115 115 114
114 113 113 113 113 112 112 111 110 109 108 108 107 107
106 106 105 105 104 103 103 102 102 101 100 -1 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

95 95 95 95 95 95 95 95 95 96 96 96 97
97 97 97 97 97 97 97 96 96 96 96 96 96 95
95 95 95 95 95 95 96 96 97 97 97 97 97 98
98 99 99 100 -1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
100 99 98 97 96 95 94 93 92 92 91 90 90
89 88 87 86 85 84 83 83 82 81 80 79 78 78
77 76 75 74 73 72 72 71 71 70 69 68 67 67
66 66 65 65 -1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0

```
  140  139  139  138  138  137  137  137  136  135  135  134  134  133
133  132  132  131  131  130  130  130  129  129  128  127  127  126
125  125  124  124  123  123  122  122  121  121   -1    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
   99   99   98   98   97   97   96   95   95   95   94   94   93
93   92   92   91   91   90   90   89   88   88   87   87   87   86
86   86   85   85   84   84   83   83   82   82   81   -1    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0

  121  120  120  119  119  118  118  117  117  116  116  115  115  114
113  113  112  112  111  110  110  109  109  108  108  107  107  106
105  104  104  103  102  102  101  101  101  100   -1    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
   81   81   80   80   79   79   78   78   77   77   76   76   75
75   75   74   74   73   73   73   72   72   71   71   70   70   69
69   69   69   68   68   68   67   67   66   65   65   -1    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0

  100  100  100  100  100  100  100  100  101  101  101  101  102  102
103  103  104  104  105  105  106  106  107  107  108  108  109  110
111  111  112  112  113  113  114  114  115  115  116  116  117  118
118  119  119  120   -1    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
   65   64   63   62   61   60   59   58   58   57   56   55   55
54   54   53   53   52   52   51   51   50   50   49   49   48   48
48   48   47   47   46   46   45   45   44   44   43   43   42   42
42   41   41   40   40   -1    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0

  120  120  121  121  121  121  121  122  122  123  124  124  125  126
126  127  127  128  129  129  130  130  131  132  132  133  134  134
135  136  137  137  138  139  139  140  140  141  142  143  143  144
144  145  145  146  146  147  148  149   -1    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
   40   39   39   38   37   36   35   35   34   34   34   33   33
33   32   32   31   31   31   30   30   29   29   29   28   28   28
27   27   27   27   26   26   26   25   25   24   24   24   24   23
23   22   22   21   21   20   20   20   20   -1    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0

  149  150  150  151  151  152  152  153  154  154  155  155  156  156
157  158  158  159  159  160  161  161  162  163  163  164  164  165
165  166  166  167  167  168  168  169  169  169  170  170  170    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0
```

```
    20    20    19    19    18    18    17    17    17    16    16    15    15
14    14    14    13    13    12    12    12    11    11    11    10    10    9
9     8     8     7     7     6     6     5     5     4     3     3     2     1
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0
```

Link	Downstream	Upstream1	Upstream2
1	17	0	0
2	3	0	0
3	13	2	0
4	5	0	0
5	12	4	0
6	11	0	0
7	8	0	0
8	10	7	0
9	10	0	0
10	11	9	8
11	12	6	10
12	13	11	5
13	16	3	12
14	15	0	0
15	16	14	0
16	17	13	15
17	18	16	1
18	0	17	0

SUMMARY OF FLOW OUTPUT
======================

Peak Discharge (m3/s)......................................=
39.60
Time to Peak (min)..=
278.99
Initial Surface Volume (m3).................................=
0.00
Volume of Rainfall - retention (m3)........................=
1506941.63
Volume leaving the Watershed (m3)..........................=
427388.88
Percentage of Vout to Vin..................................=
28.36
Final Surface Volume (m3)..................................=
49218.38
Volume Infiltrated (m3)....................................=
1030327.75
Percentage of Vinftot to Vin...............................=
68.37
Percent Mass Balance...................................... =
0.00

HYDROLOGICAL VARIABLES MINIMUM AND MAXIMUM VALUES
===

Min. Rainfall Intensity (mm/hr)............................=
0.00
Max. Rainfall Intensity (mm/hr)............................=

```
51.62
Min. Infiltration Depth (mm)...............................=
0.00
Max. Infiltration Depth (mm)...............................=
114.75
Min. Overland Depth (m)....................................=
0.00
Max. Overland Depth (m)....................................=
0.41
Min. Channel Depth (m).....................................=
0.00
Max. Channel Depth (m).....................................=
1.87


SUMMARY OF SEDIMENT OUTPUT : Volume in Cubic Meters
(Percentages from the total eroded
===================================================

Total Volume of Sand Eroded................................=
622.36
Total Volume of Silt Eroded................................=
1321.16
Total Volume of Clay Eroded................................=
385.80
Total Volume of Material Eroded............................=
2329.33

Volumes of Eroded Sediment Remaining on the Overland:
----------------------------------------------------
Total Volume of Suspended Sand.............................=
0.00 ->  0.00 %
Total Volume of Suspended Silt.............................=
0.00 ->  0.00 %
Total Volume of Suspended Clay.............................=
1.42 ->  0.37 %
Total Volume of Suspended Sediment.........................=
1.42 ->  0.06 %

Total Volume of Deposited Sand.............................=
518.65 -> 83.34 %
Total Volume of Deposited Silt.............................=
945.72 -> 71.58 %
Total Volume of Deposited Clay.............................=
17.27 ->  4.48 %
Total Volume of Deposited Sediment.........................=
1481.64 -> 63.61 %

Total Volume of Sand Remaining on the Overland.............=
518.65 -> 83.34 %
Total Volume of Silt Remaining on the Overland.............=
945.73 -> 71.58 %
Total Volume of Clay Remaining on the Overland.............=
18.69 ->  4.84 %
Total Volume of Eroded Material Remaining on the Overland..=
1483.07 -> 63.67 %

Volumes of Eroded Sediment Remaining in the Channels:
```

```
----------------------------------------------------
Total Volume of Suspended Sand.............................=
0.10 ->  0.02 %
Total Volume of Suspended Silt.............................=
2.97 ->  0.23 %
Total Volume of Suspended Clay.............................=
29.65 ->  7.68 %
Total Volume of Suspended Sediment.........................=
32.72 ->  1.40 %

Total Volume of Deposited Sand.............................=
78.12 -> 12.55 %
Total Volume of Deposited Silt.............................=
93.56 ->  7.08 %
Total Volume of Deposited Clay.............................=
0.33 ->  0.09 %
Total Volume of Deposited Sediment.........................=
172.01 ->  7.38 %

Total Volume of Sand Remaining in the Channels.............=
78.21 -> 12.57 %
Total Volume of Silt Remaining in the Channels.............=
96.54 ->  7.31 %
Total Volume of Clay Remaining in the Channels.............=
29.98 ->  7.77 %
Total Volume of Eroded Material Remaining in the Channels..=
204.73 ->  8.79 %

Volumes of Eroded Sediment Leaving the Watershed:
----------------------------------------------------
Total Volume of Eroded Sand Leaving the Watershed..........=
25.50 ->  4.10 %
Total Volume of Eroded Silt Leaving the Watershed..........=
278.83 -> 21.11 %
Total Volume of Eroded Clay Leaving the Watershed..........=
337.11 -> 87.38 %
Total Volume of Eroded Material Leaving the Watershed......=
641.45 -> 27.54 %

Percent Mass Balance.......................................=
-0.00


SEDIMENT VARIABLES MINIMUM AND MAXIMUM VALUES
============================================

Max. Flux Conc. Overland (m3/s/m3/s).....................= 0.400694
Max. Flux Conc. Channels (m3/s/m3/s).....................= 0.00857151
Max. Suspended Sediment in Overland (mm).................= 1.5874
Max. Suspended Sediment in Channels (mm).................= 7.29075
Max. Concentration on Overland (m3/m3)...................= 0.0314505
Max. Concentration in Channels (m3/m3)...................= 0.00659597
Total Net Volume (mm) at the End of the Simulation:
    Minimum vValue ......................................=
-49.905
    Maximum Value .......................................=
32.361
    Mean ................................................=
```

```
-0.033
    Standard Deviation ..................................=
1.016

Program stops at simulation minute:    700.00

CASC2D RUNNING TIME:    292.96 minutes
```

```
#############  INPUT DATA FILES  #############
CONTROL                     Input/runW2.dat
PRECIP                      Input/15minAver.pre
CHANNEL                     input/chann0.035.dat

#############  INPUT DATA GRIDS  #############
ELEVATION                   Input/DEM10.asc
SOIL                        Input/soil.asc
LANDUSE                     Input/landuse.asc
MASK                        Input/mask.asc
LINK                        Input/link.asc
NODE                        Input/node.asc

##############  OUTPUT FILES  ################
SUMMARY                     Output/run2.sum
DISCHARGE_OUT               Output/run2.q
SEDIMENT_OUT                Output/run2.qs

######  OUTPUT TIME SERIES GRID NAMES  #######
RAINFALL                    HyrOutMaps/rain
INF_DEPTH                   HyrOutMaps/infvol
WATER_DEPTH                 HyrOutMaps/depth
SED_CONC                    HyrOutMaps/conc
EROS_DEP                    SEDOutMaps/netvol
SAND_FLUX_OUT               SEDOutMaps/fluxSAND
SILT_FLUX_OUT               SEDOutMaps/fluxSILT
CLAY_FLUX_OUT               SEDOutMaps/fluxCLAY
TOTAL_FLUX_OUT              SEDOutMaps/fluxTOT
```

```
0.25 43200  43200  240  240
48   9  0.01524
1
1

1
2             3600
278397.16     4562325.19
279029.12     4562334.95

1  0
0.04          1.00          0.0005        1

1  1  1
0.35          20            0.27          0.25          0.61
0.14          0.48

1  1  3
48            9             27.84

1  1  2
48            9             27.84
```

```
0.0 0.0
0.08    0.08
0.05    0.05
0.19    0.19
1.73    1.73
1.35    1.35
2.06    2.06
0.52    0.52
0.31    0.31
0.28    0.28
0.14    0.14
0.05    0.05
0.33    0.33
```

```
1   11  4
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   11  12
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
3   7   8
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
4   11  10
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
2   4.4 3.5 0   0.020   1
5   4   4
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
6   4   12
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
2   2.8 2   0   0.020   1
7   1   9
2   2.8 2   0   0.020   1
8   7   13
2   4.4 3.5 0   0.020   1
```

```
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
9    5   8
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
10   6   9
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
11   7   10
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
12   2   13
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
13   1   14
2    4.4 3.5 0    0.020    1
14   16  0
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
2    4.4 3.5 0    0.020    1
15   11  14
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
2    2.8 2   0    0.020    1
```

```
2    2.8 2   0   0.020   1
2    2.8 2   0   0.020   1
2    2.8 2   0   0.020   1
16   3   11
2    2.8 2   0   0.020   1
2    2.8 2   0   0.020   1
2    2.8 2   0   0.020   1
17   2   11
2    2.8 2   0   0.020   1
2    2.8 2   0   0.020   1
```

```
CONTROL Input Data
==================
Control file : Input/runW2.dat
DT = 0.25 sec NITER= 43200 NITRN = 43200 NPRN = 240 NPLT = 240

Overland outlet cell:
JOUT = 48 KOUT = 9 SOVOUT = 0.01524

CHANCHECK= 1
ELCONV = 1.00

Rainfall Data
=============
IRAIN = 1
Rainfall file: Input/15minAver.pre
NRG = 2 NREAD = 3600
XRG[1] = 278397.156250  YRG[1] = 4562325.000000
XRG[2] = 279029.125000  YRG[2] = 4562335.000000

Land Use Parameters
===================
NMAN = 1 INDEXSDEP = 0

    Index   Manning    Intercept.   Cusle   Pusle
    -----   -- n --    -- [mm] --   -----   -----
      1      0.040       1.000  0.001   1.000

Soil type Parameters
====================
INDEXINF= 1 INDEXEROS= 1 NSOIL= 1

        Index    Ks        G          Md        %Sand      %Silt
%Clay     Kusle
        -----  [cm/h]    [cm]        -----      -----      -----
-----     -----
         1     0.350    20.000      0.270      0.250      0.610
0.140     0.480

Internal Gages Data
-------------------
INDEXDIS = 1  NDIS = 1  Q_units = 3

        Gage      Row      Column      Area
        ----      ---      ------     [has]
         1        48         9        27.840

Internal Sediment Gages Data
----------------------------
INDEXSED = 1  NSED = 1 Qs_Units = 2

        Gage      Row      Column      Area
        ----      ---      ------     [has]
         1        48         9        27.840

ASCII grid files header
-------------------------
ncols        76
```

```
nrows        60
xllcorner    278319.00
yllcorner    4561804.00
cellsize     10.00
NODATA_value     -9999

The following Grids have been read:
 ------------------------------

Elevation Grid: Input/DEM10.asc
Shape Grid:     Input/mask.asc
Soils Grid:     Input/soil.asc
Landuse Grid:   Input/landuse.asc
Node Grid:  Input/node.asc
Link Grid:  Input/link.asc

Number of cells in basin: 2784
Basin area: 27.840 [ha]

Channel Linkage Information
---------------------------

Maximum Number of Links = 17
Maximum Number of Nodes = 18

   15   16   16   17   18   19   20   21   22   23   24   25   -1
0   0    0    0    0
   60   59   58   58   58   58   57   57   56   55   54   53   -1
0   0    0    0    0

   23   24   25   26   27   28   29   30   31   32   33   34   -1
0   0    0    0    0
   25   25   25   25   25   25   25   25   25   25   25   24   -1
0   0    0    0    0

   24   25   26   27   28   29   30   31   -1    0    0    0    0
0   0    0    0    0
   31   31   31   31   31   31   31   31   -1    0    0    0    0
0   0    0    0    0

   25   26   27   28   28   29   30   30   30   30   30   31   -1
0   0    0    0    0
   53   52   51   50   49   48   47   46   45   44   43   42   -1
0   0    0    0    0

   27   26   25   25   25   -1    0    0    0    0    0    0    0
0   0    0    0    0
   57   56   55   54   53   -1    0    0    0    0    0    0    0
0   0    0    0    0

   30   31   32   33   34   -1    0    0    0    0    0    0    0
0   0    0    0    0
   24   24   24   24   24   -1    0    0    0    0    0    0    0
0   0    0    0    0

   30   31   -1    0    0    0    0    0    0    0    0    0    0
0   0    0    0    0
   37   36   -1    0    0    0    0    0    0    0    0    0    0
0   0    0    0    0
```

```
    31    32    33    34    34    35    35    36    -1     0     0     0     0
0    0     0     0     0
    31    30    29    28    27    26    25    24    -1     0     0     0     0
0    0     0     0     0

    31    31    31    31    31    31    -1     0     0     0     0     0     0
0    0     0     0     0
    36    35    34    33    32    31    -1     0     0     0     0     0     0
0    0     0     0     0

    31    31    31    31    31    31    31    -1     0     0     0     0     0
0    0     0     0     0
    42    41    40    39    38    37    36    -1     0     0     0     0     0
0    0     0     0     0

    38    37    36    35    34    33    32    31    -1     0     0     0     0
0    0     0     0     0
    47    46    45    45    44    44    43    42    -1     0     0     0     0
0    0     0     0     0

    34    35    36    -1     0     0     0     0     0     0     0     0     0
0    0     0     0     0
    24    24    24    -1     0     0     0     0     0     0     0     0     0
0    0     0     0     0

    36    37    -1     0     0     0     0     0     0     0     0     0     0
0    0     0     0     0
    24    23    -1     0     0     0     0     0     0     0     0     0     0
0    0     0     0     0

    37    38    38    39    39    39    40    41    42    43    44    45    45
46   47    48     0     0
    23    22    21    20    19    18    17    16    15    14    13    12    11
10    9     9     0     0

    41    40    40    39    39    38    37    37    37    37    37    37    -1
0    0     0     0     0
    34    33    32    31    30    29    28    27    26    25    24    23    -1
0    0     0     0     0

    41    40    39    38    -1     0     0     0     0     0     0     0     0
0    0     0     0     0
    47    47    47    47    -1     0     0     0     0     0     0     0     0
0    0     0     0     0

    40    39    38    -1     0     0     0     0     0     0     0     0     0
0    0     0     0     0
    49    48    47    -1     0     0     0     0     0     0     0     0     0
0    0     0     0     0

 Link     Downstream     Upstream1    Upstream2     Upstream3
Upstream4     Upstream5     Upstream6     Upstream7

   1            4             0            0             0
0            0             0            0
   2            12            0            0             0
0            0             0            0
```

```
    3         8         0         0         0
0         0         0         0
    4        10         5         1         0
0         0         0         0
    5         4         0         0         0
0         0         0         0
    6        12         2         2         0
0         0         0         0
    7         9        10         0         0
0         0         0         0
    8        13         3         9         0
0         0         0         0
    9         8        10         7         0
0         0         0         0
   10         9         4        11         0
0         0         0         0
   11        10        16        17         0
0         0         0         0
   12        13         6         2         8
0         0         0         0
   13        14        12         8        15
0         0         0         0
   14         0        15        13         0
0         0         0         0
   15        14         0         0         0
0         0         0         0
   16        11         0         0         0
0         0         0         0
   17        11         0         0         0
0         0         0         0

SUMMARY OF FLOW OUTPUT
======================

Peak Discharge (m3/s)......................................=
2.53
Time to Peak (min).........................................=
105.35
Initial Surface Volume (m3)................................=
0.00
Volume of Rainfall - retention (m3)........................=
11674.08
Volume leaving the Watershed (m3)..........................=
3732.75
Percentage of Vout to Vin..................................=
31.97
Final Surface Volume (m3)..................................=
122.11
Volume Infiltrated (m3)....................................=
7817.27
Percentage of Vinftot to Vin...............................=
66.96
Percent Mass Balance...................................... =
0.02

HYDROLOGICAL VARIABLES MINIMUM AND MAXIMUM VALUES
================================================
```

```
Min. Rainfall Intensity (mm/hr)............................=
0.00
Max. Rainfall Intensity (mm/hr)............................=
52.32
Min. Infiltration Depth (mm)...............................=
0.00
Max. Infiltration Depth (mm)...............................=
32.08
Min. Overland Depth (m)....................................=
0.00
Max. Overland Depth (m)....................................=
0.33
Min. Channel Depth (m).....................................=
0.00
Max. Channel Depth (m).....................................=
0.49


SUMMARY OF SEDIMENT OUTPUT : Volume in Cubic Meters
(Percentages from the total eroded
===================================================

Total Volume of Sand Eroded................................=
89.72
Total Volume of Silt Eroded................................=
218.92
Total Volume of Clay Eroded................................=
50.24
Total Volume of Material Eroded............................=
358.88

Volumes of Eroded Sediment Remaining on the Overland:
----------------------------------------------------
Total Volume of Suspended Sand.............................=
0.00 ->  0.00 %
Total Volume of Suspended Silt.............................=
0.00 ->  0.00 %
Total Volume of Suspended Clay.............................=
0.21 ->  0.43 %
Total Volume of Suspended Sediment.........................=
0.22 ->  0.06 %

Total Volume of Deposited Sand.............................=
77.64 -> 86.53 %
Total Volume of Deposited Silt.............................=
123.14 -> 56.25 %
Total Volume of Deposited Clay.............................=
0.75 ->  1.48 %
Total Volume of Deposited Sediment.........................=
201.52 -> 56.15 %

Total Volume of Sand Remaining on the Overland.............=
77.64 -> 86.53 %
Total Volume of Silt Remaining on the Overland.............=
123.14 -> 56.25 %
Total Volume of Clay Remaining on the Overland.............=
0.96 ->  1.91 %
Total Volume of Eroded Material Remaining on the Overland..=
```

```
201.74 -> 56.21 %

Volumes of Eroded Sediment Remaining in the Channels:
-----------------------------------------------------
Total Volume of Suspended Sand.............................=
0.00 ->  0.00 %
Total Volume of Suspended Silt.............................=
0.00 ->  0.00 %
Total Volume of Suspended Clay.............................=
0.04 ->  0.08 %
Total Volume of Suspended Sediment.........................=
0.04 ->  0.01 %

Total Volume of Deposited Sand.............................=
10.69 -> 11.92 %
Total Volume of Deposited Silt.............................=
6.82 ->  3.12 %
Total Volume of Deposited Clay.............................=
0.01 ->  0.02 %
Total Volume of Deposited Sediment.........................=
17.52 ->  4.88 %

Total Volume of Sand Remaining in the Channels.............=
10.69 -> 11.92 %
Total Volume of Silt Remaining in the Channels.............=
6.82 ->  3.12 %
Total Volume of Clay Remaining in the Channels.............=
0.05 ->  0.10 %
Total Volume of Eroded Material Remaining in the Channels..=
17.56 ->  4.89 %

Volumes of Eroded Sediment Leaving the Watershed:
-----------------------------------------------------
Total Volume of Eroded Sand Leaving the Watershed..........=
1.39 ->  1.55 %
Total Volume of Eroded Silt Leaving the Watershed..........=
88.95 -> 40.63 %
Total Volume of Eroded Clay Leaving the Watershed..........=
49.23 -> 97.99 %
Total Volume of Eroded Material Leaving the Watershed......=
139.58 -> 38.89 %

Percent Mass Balance.......................................=
-0.00


SEDIMENT VARIABLES MINIMUM AND MAXIMUM VALUES
=============================================

Max. Flux Conc. Overland (m3/s/m3/s).......................= 0.727331
Max. Flux Conc. Channels (m3/s/m3/s).......................= 0.164423
Max. Suspended Sediment in Overland (mm)...................= 3.49083
Max. Suspended Sediment in Channels (mm)...................= 13.315
Max. Concentration on Overland (m3/m3).....................= 0.240675
Max. Concentration in Channels (m3/m3).....................= 0.140711
Total Net Volume (mm) at the End of the Simulation:
    Minimum vValue ........................................=
-122.872
```

```
    Maximum Value .......................................=
84.448
    Mean ................................................=
-0.502
    Standard Deviation ..................................=
6.147

Program stops at simulation minute:    180.00

CASC2D RUNNING TIME:     13.02 minutes
```

```
#############  INPUT DATA FILES  #############
CONTROL                      Input/runW3.dat
PRECIP                       Input/15minAver.pre
CHANNEL                      input/chann0.035.dat

#############  INPUT DATA GRIDS  #############
ELEVATION                    Input/DEM10.asc
SOIL                         Input/soil.asc
LANDUSE                      Input/landuse.asc
MASK                         Input/mask.asc
LINK                         Input/link.asc
NODE                         Input/node.asc

##############  OUTPUT FILES  ###############
SUMMARY                      Output/run2.sum
DISCHARGE_OUT                Output/run2.q
SEDIMENT_OUT                 Output/run2.qs

######  OUTPUT TIME SERIES GRID NAMES  #######
RAINFALL                     HyrOutMaps/rain
INF_DEPTH                    HyrOutMaps/infvol
WATER_DEPTH                  HyrOutMaps/depth
SED_CONC                     HyrOutMaps/conc
EROS_DEP                     SEDOutMaps/netvol
SAND_FLUX_OUT                SEDOutMaps/fluxSAND
SILT_FLUX_OUT                SEDOutMaps/fluxSILT
CLAY_FLUX_OUT                SEDOutMaps/fluxCLAY
TOTAL_FLUX_OUT               SEDOutMaps/fluxTOT
```

```
 0.25 43200  32400  240  240
 8    68 0.01616
 1
 1

 1
 2             3600
 279073.31     4565291.23
 278501.24     4564429.24

 1  0
 0.20          0.76          0.0005        1

 1  1  1
 0.85          25            0.20          0.25          0.61
0.14          0.40

 1  1  3
 8             68            47.79

 1  1  2
 8             68            47.79
```

```
0.46      0.46
0.96      0.96
2.08      2.08
1.80      1.80
0.49      0.49
0.24      0.24
0.20      0.20
0.19      0.19
0.13      0.13
```

```
1    21   0
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
3    18   1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
4    21   2
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
```

```
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
5    20   2
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
6    1    5
2    2.8 2    0    0.035    1
7    12   4
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
8    21   4
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
```

```
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
9    27   5
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
10   3    7
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
11   5    7
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
2    4.4 3.5 0    0.035    1
12   9    10
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
2    2.8 2    0    0.035    1
```

```
13   9    10
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
14   8    11
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
2    4.4  3.5  0    0.035    1
15   2    11
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
16   1    17
2    2.8  2    0    0.035    1
17   1    14
2    2.8  2    0    0.035    1
18   7    17
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
19   8    17
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
20   4    9
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
2    2.8  2    0    0.035    1
21   1    9
2    2.8  2    0    0.035    1
```

```
CONTROL Input Data
==================
Control file : Input/runW3.dat
DT = 0.25 sec NITER= 43200 NITRN = 32400 NPRN = 240 NPLT = 240

Overland outlet cell:
JOUT = 8 KOUT = 68 SOVOUT = 0.01616

CHANCHECK= 1
ELCONV = 1.00

Rainfall Data
=============
IRAIN = 1
Rainfall file: Input/15minAver.pre
NRG = 2 NREAD = 3600
XRG[1] = 279073.312500   YRG[1] = 4565291.000000
XRG[2] = 278501.250000   YRG[2] = 4564429.000000

Land Use Parameters
===================
NMAN = 1 INDEXSDEP = 0

    Index   Manning    Intercept.   Cusle   Pusle
    -----   -- n --    -- [mm] --   -----   -----
      1      0.200       0.760   0.001    1.000

Soil type Parameters
====================
INDEXINF= 1 INDEXEROS= 1 NSOIL= 1

        Index    Ks        G          Md         %Sand       %Silt
%Clay     Kusle
        -----  [cm/h]    [cm]        -----       -----       -----
-----     -----
          1     0.850    25.000      0.200       0.250       0.610
0.140     0.400

Internal Gages Data
-------------------
INDEXDIS = 1  NDIS = 1  Q_units = 3

        Gage       Row      Column      Area
        ----       ---      ------      [has]
          1         8        68         47.790

Internal Sediment Gages Data
----------------------------
INDEXSED = 1  NSED = 1 Qs_Units = 2

        Gage       Row      Column      Area
        ----       ---      ------      [has]
          1         8        68         47.790

ASCII grid files header
-------------------------
ncols       92
```

```
nrows        99
xllcorner    278415.38
yllcorner    4564356.00
cellsize     10.00
NODATA_value     -9999

The following Grids have been read:
 -------------------------------
Elevation Grid: Input/DEM10.asc
Shape Grid:     Input/mask.asc
Soils Grid:     Input/soil.asc
Landuse Grid:   Input/landuse.asc
Node Grid:  Input/node.asc
Link Grid:  Input/link.asc

Number of cells in basin: 4849
Basin area: 48.490 [ha]

Channel Linkage Information
---------------------------

Maximum Number of Links = 21
Maximum Number of Nodes = 29

   28   27   26   25   24   23   22   21   20   19   18   17   16
15   14   13   12   11   10    9    8    0    0    0    0    0    0
0    0
   62   62   63   63   63   64   64   64   65   65   65   66   66
66   67   67   67   68   68   68   68    0    0    0    0    0    0
0    0

   32   31   30   29   28   -1    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0
   61   61   61   61   62   -1    0    0    0    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0

   38   37   36   35   35   35   34   33   32   32   32   32   32
31   31   31   30   29   28   -1    0    0    0    0    0    0    0
0    0
   80   79   78   77   76   75   74   73   72   71   70   69   68
67   66   65   64   63   62   -1    0    0    0    0    0    0    0
0    0

   52   51   50   49   48   47   46   45   44   43   42   41   41
40   39   38   37   36   35   34   33   32   -1    0    0    0    0
0    0
   48   48   48   48   49   49   49   50   50   51   52   53   54
55   56   57   58   58   59   59   60   61   -1    0    0    0    0
0    0

   52   51   50   49   48   47   46   45   44   43   42   41   40
39   38   37   36   35   34   33   32   -1    0    0    0    0    0
0    0
   68   67   67   66   65   64   63   63   63   63   62   62   62
62   62   62   62   62   62   61   61   -1    0    0    0    0    0
0    0
```

```
    52    52    -1     0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
    69    68    -1     0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

    62    62    61    61    60    59    58    57    56    55    54    53    52
-1     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
    37    38    39    40    41    42    43    44    45    46    46    47    48
-1     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

    73    72    71    70    69    68    67    66    65    64    63    62    61
60    59    58    57    56    55    54    53    52    -1     0     0     0     0
0     0
    51    51    51    52    52    52    52    52    52    52    52    51    50
50    50    50    50    50    49    48    48    48    -1     0     0     0     0
0     0

    79    78    77    76    75    74    73    72    71    70    69    68    67
66    65    64    63    62    61    60    59    58    57    56    55    54    53
52    -1
    68    68    68    68    68    69    69    69    69    69    69    69    69
69    69    69    69    69    69    69    69    69    69    68    68    68    68
68    -1

    64    64    63    62    -1     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
    34    35    36    37    -1     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

    67    66    65    64    63    62    -1     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
    36    36    36    37    37    37    -1     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

    64    64    64    64    64    64    64    64    64    64    -1     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
    25    26    27    28    29    30    31    32    33    34    -1     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

    70    70    69    69    68    68    67    66    65    64    -1     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
    26    27    28    29    30    31    32    33    33    34    -1     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

    75    74    73    72    71    70    69    68    67    -1     0     0     0
```

```
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      32    33    33    34    34    34    35    35    36    -1    0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      69    68    67    -1    0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      36    36    36    -1    0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      76    76    -1    0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      31    32    -1    0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      76    75    -1    0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      32    32    -1    0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      83    82    81    80    79    78    77    76    -1    0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      25    26    27    28    29    30    31    32    -1    0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      84    83    82    81    80    79    78    77    76    -1    0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      25    26    27    28    29    30    31    32    32    -1    0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      83    82    81    80    79    -1    0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      68    68    68    68    68    -1    0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

      80    79    -1    0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0
      69    68    -1    0     0     0     0     0     0     0     0     0     0
0     0     0     0     0     0     0     0     0     0     0     0     0     0
0     0

 Link     Downstream     Upstream1    Upstream2     Upstream3
Upstream4     Upstream5    Upstream6     Upstream7
```

1	0	3	2	0
0	0	0	0	
2	1	5	4	0
0	0	0	0	
3	1	0	0	0
0	0	0	0	
4	2	8	7	0
0	0	0	0	
5	2	9	6	0
0	0	0	0	
6	5	9	0	0
0	0	0	0	
7	4	11	10	0
0	0	0	0	
8	4	0	0	0
0	0	0	0	
9	5	20	21	0
0	0	0	0	
10	7	12	13	0
0	0	0	0	
11	7	15	14	0
0	0	0	0	
12	10	0	0	0
0	0	0	0	
13	10	0	0	0
0	0	0	0	
14	11	17	16	0
0	0	0	0	
15	11	14	0	0
0	0	0	0	
16	17	18	19	0
0	0	0	0	
17	14	19	16	18
0	0	0	0	
18	17	19	0	0
0	0	0	0	
19	17	0	0	0
0	0	0	0	
20	9	0	0	0
0	0	0	0	
21	9	20	20	0
0	0	0	0	

SUMMARY OF FLOW OUTPUT
====================

Peak Discharge (m3/s)..=
1.16
Time to Peak (min)...=
65.51
Initial Surface Volume (m3)..................................=
0.00
Volume of Rainfall - retention (m3)..........................=
19807.15
Volume leaving the Watershed (m3)............................=
1627.64
Percentage of Vout to Vin....................................=
8.22

```
Final Surface Volume (m3)..................................=
52.65
Volume Infiltrated (m3)....................................=
18125.35
Percentage of Vinftot to Vin...............................=
91.51
Percent Mass Balance...................................... =
0.01

HYDROLOGICAL VARIABLES MINIMUM AND MAXIMUM VALUES
==================================================

Min. Rainfall Intensity (mm/hr)............................=
0.00
Max. Rainfall Intensity (mm/hr)............................=
52.83
Min. Infiltration Depth (mm)...............................=
0.00
Max. Infiltration Depth (mm)...............................=
62.32
Min. Overland Depth (m)....................................=
0.00
Max. Overland Depth (m)....................................=
0.05
Min. Channel Depth (m).....................................=
0.00
Max. Channel Depth (m).....................................=
0.73


SUMMARY OF SEDIMENT OUTPUT : Volume in Cubic Meters
(Percentages from the total eroded
===================================================

Total Volume of Sand Eroded................................=
11.54
Total Volume of Silt Eroded................................=
28.17
Total Volume of Clay Eroded................................=
6.46
Total Volume of Material Eroded............................=
46.17

Volumes of Eroded Sediment Remaining on the Overland:
----------------------------------------------------
Total Volume of Suspended Sand.............................=
0.00 ->  0.00 %
Total Volume of Suspended Silt.............................=
0.00 ->  0.00 %
Total Volume of Suspended Clay.............................=
0.06 ->  1.00 %
Total Volume of Suspended Sediment.........................=
0.06 ->  0.14 %

Total Volume of Deposited Sand.............................=
10.24 -> 88.68 %
Total Volume of Deposited Silt.............................=
20.99 -> 74.52 %
```

```
Total Volume of Deposited Clay............................=
0.47 ->  7.33 %
Total Volume of Deposited Sediment........................=
31.70 -> 68.66 %

Total Volume of Sand Remaining on the Overland............=
10.24 -> 88.68 %
Total Volume of Silt Remaining on the Overland............=
20.99 -> 74.53 %
Total Volume of Clay Remaining on the Overland............=
0.54 ->  8.33 %
Total Volume of Eroded Material Remaining on the Overland..=
31.77 -> 68.80 %

Volumes of Eroded Sediment Remaining in the Channels:
----------------------------------------------------
Total Volume of Suspended Sand............................=
0.00 ->  0.00 %
Total Volume of Suspended Silt............................=
0.00 ->  0.00 %
Total Volume of Suspended Clay............................=
0.15 ->  2.35 %
Total Volume of Suspended Sediment........................=
0.15 ->  0.33 %

Total Volume of Deposited Sand............................=
0.97 ->  8.43 %
Total Volume of Deposited Silt............................=
0.85 ->  3.02 %
Total Volume of Deposited Clay............................=
0.02 ->  0.30 %
Total Volume of Deposited Sediment........................=
1.84 ->  3.99 %

Total Volume of Sand Remaining in the Channels............=
0.97 ->  8.43 %
Total Volume of Silt Remaining in the Channels............=
0.85 ->  3.02 %
Total Volume of Clay Remaining in the Channels............=
0.17 ->  2.65 %
Total Volume of Eroded Material Remaining in the Channels..=
1.99 ->  4.32 %

Volumes of Eroded Sediment Leaving the Watershed:
----------------------------------------------------
Total Volume of Eroded Sand Leaving the Watershed.........=
0.33 ->  2.89 %
Total Volume of Eroded Silt Leaving the Watershed.........=
6.32 -> 22.45 %
Total Volume of Eroded Clay Leaving the Watershed.........=
5.75 -> 89.00 %
Total Volume of Eroded Material Leaving the Watershed.....=
12.41 -> 26.88 %

Percent Mass Balance......................................=
-0.00
```

```
SEDIMENT VARIABLES MINIMUM AND MAXIMUM VALUES
=============================================

Max. Flux Conc. Overland (m3/s/m3/s).....................= 0.403292
Max. Flux Conc. Channels (m3/s/m3/s).....................= 0.0622199
Max. Suspended Sediment in Overland (mm)..................= 0.662872
Max. Suspended Sediment in Channels (mm)..................= 2.9734
Max. Concentration on Overland (m3/m3)...................= 0.0433778
Max. Concentration in Channels (m3/m3)...................= 0.0404315
Total Net Volume (mm) at the End of the Simulation:
    Minimum vValue .......................................=
-5.642
    Maximum Value ........................................=
5.789
    Mean .................................................=
-0.026
    Standard Deviation ...................................=
0.408

Program stops at simulation minute:    180.00

CASC2D RUNNING TIME:     16.97 minutes
```