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THE TWO-DIMENSIONAL UPLAND EROSION MODEL CASC2D-SED[1]

Billy E. Johnson, Pierre Y. Julien, Darcy K. Molnar, and Chester C. Watson[2]

ABSTRACT: The two-dimensional soil erosion model CASC2D-SED simulates the dynamics of upland erosion during single rainstorms. The model is based on the raster-based surface runoff calculations from CASC2D. Rainfall precipitation is distributed in time and space. Infiltration is calculated from the Green-Ampt equations. Surface runoff is calculated from the diffusive wave approximation to the Saint-Venant equations in two-dimensions. Watershed data bases in raster Geographical Information System (GIS) provide information on the soil type, size fractions, soil erodibility, cropping management, and conservation practice factors for soil erosion calculations. Upland sediment transport is calculated for the size fractions (sand, silt, and clay), and the model displays the sediment flux, the amount of suspended sediment, and the net erosion and deposition using color graphics. The model has been tested on Goodwin Creek, Mississippi. The peak discharge and time to peak are within ± 20 percent and sediment transport rates within -50 percent to 200 percent.

(KEY TERMS: erosion; sedimentation; hydraulics; hydrograph; analysis and modeling; surface water hydrology.)

INTRODUCTION

Accelerated soil erosion is a widely recognized global problem. Erosion encompasses a series of complex and interrelated natural processes that have the effect of loosening and moving away soil and rock materials under the action of water, wind, and other geologic agents. Long term erosion effects include denudation of the land surface, i.e., the removal of soil and rock particles from exposed surfaces, their transport to lower elevations, and eventual deposition. Sediment has a threefold effect on the environment: (a) depleting the productive capacity of the land from which it is transported; (b) impairing the quality of the water in which it is transported; and (c) aggrading the land on which it is deposited.

A quantitative analysis of the amount of sediment supplied to a stream from the watershed is usually difficult to perform because of the complexity of the physical processes involved and the spatial and temporal variability of all the parameters describing local rainstorms, surface runoff, upland erosion, and bank erosion processes.

Sediment sources denote the total amount of sediment eroded on a watershed on an annual basis, also called "annual gross erosion". The annual gross erosion A_T depends on the source of sediment in terms of upland erosion A_U, gully erosion A_G, and local bank erosion A_B; thus, $A_T = A_U + A_G + A_B$.

Erosion and sedimentation by water embody the processes of detachment, transportation, and deposition of soil particles by the erosive and transport agents of raindrop impact and runoff over the soil surface. The major factors affecting upland erosion processes are: hydrology, topography, soil erodibility, soil transportability, vegetation cover, incorporated residue, residual land use, subsurface effects, tillage, roughness, and tillage marks (Foster, 1982).

Modeling soil erosion is the process of mathematically describing soil particle detachment, transport, and deposition on land surfaces. There are at least three reasons for modeling erosion: (a) erosion models can be used as predictive tools for assessing soil loss for conservation planning, project planning, soil erosion inventories, and for regulation; (b) physically-based mathematical models can predict where and when erosion is occurring, thus helping the

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[2] Respectively, Research Hydraulic Engineer, U.S. Army Corps of Engineers, 3909 Halls Ferry Road, Vicksburg, Mississippi 39180; and Professor, Research Scientist, and Post-Doctoral Fellow, Colorado State University, Engineering Research Center, Room A221, Fort Collins, Colorado 80523 (E-Mail/Johnson: johnson@ex1.wes.army.mil).

conservation planner to target efforts to reduce erosion; and (c) models can be used as tools for understanding erosion processes and their interactions and for setting research priorities.

Long-term upland erosion amounts (i.e., sheet and rill erosion) are commonly predicted by the Universal Soil Loss Equation, USLE. The USLE method computes annual upland soil loss due to sheet and rill erosion in tons per acre per year. The Revised Universal Soil Loss Equation (RUSLE) is an improvement over the USLE (Renard *et al.,* 1991), but still only computes annual soil loss. To compute sediment yield, in tons, for a single storm event the Modified Universal Soil Loss Equation (MUSLE) was proposed in 1972. Field tests showed that the use of the USLE equation to predict sediment yield on an event or event-series basis resulted in rather large errors when compared with field measurements (Smith, 1976).

Recent advances in hydrology, soil science, erosion mechanics, and computer technology have provided the technological basis for the development of physically-based erosion prediction technology. Physically-based models simulate watershed runoff from the equations of continuity and momentum. The diffusive wave approximation is usually appropriate for overland flow. Fundamental models have several advantages over empirical equations (Foster, 1982): (1) they are generally more physically based and consequently should be more accurately extrapolated; (2) they more accurately represent the processes; for example, rill and interrill erosion are considered separately rather than being lumped; (3) they are more accurate for single event storms; (4) they can consider more complex areas; (5) they consider deposition processes directly; and (6) they can consider channel erosion and deposition. Therefore, the development of detailed, physically-based models of the erosion/sedimentation processes, which incorporates the talents of diverse interests such as engineers, hydrologists, and agronomists, will lead to improved understanding of the mechanics of soil detachment, transport, and deposition (Foster, 1982).

The objective of this paper is to discuss the upland erosion subroutine for the two-dimensional surface runoff model CASC2D. The algorithm was tested with field measurements at several sediment gaging stations within Goodwin Creek, an 8.26 mi^2 basin located in Mississippi.

SURFACE HYDROLOGY

Surface hydrology consists of those processes that describe the distribution of rainfall, infiltration of the rainfall into the ground, and the routing of excess rainfall across the overland planes into the channels and ultimately to the watershed outlet. In this study, the two-dimensional surface runoff model CASC2D, developed by Julien *et al.* (1995), was used to calculate surface flow depth, unit discharge, and friction slope.

UPLAND EROSION

Sediment discharge by means of overland flow is a function of the hydraulic properties of flow, the physical properties of soil, and surface characteristics. Sediment transport as a result of bare soil erosion under simulated rainfall relates to the following variables (Julien, 1995):

$$q_s = f\left(S_o, q, i, X, \rho, \nu, \frac{\tau_c}{\tau_o} \right) \tag{1}$$

where, q_s = unit sediment discharge, S_o = bed slope, q = unit discharge, i = rainfall intensity, X = longitudinal distance, ρ = mass density of water, ν = kinematic viscosity of water, τ_c = critical shear stress, and τ_o = applied shear stress.

Kilinc and Richardson (1973) experimentally examined soil erosion from overland flow generated by simulated rainfall. The results of this experimental investigation, at the Colorado State University (CSU) Engineering Research Center, resulted in the following sediment transport equation for sheet and rill erosion for bare sandy soils:

$$q_s = 25500 q_o^{2.035} S_o^{1.6664} \tag{2}$$

where q_s is in (tons/m·s) and q is the unit discharge in (m^2/s).

This equation was modified after considering various soil types, vegetation cropping management factors, and conservation practices (Julien, 1995):

$$q_s = 25500 q_o^{2.035} S_f^{1.664} \frac{K}{0.15} CP \tag{3}$$

where K, C, and P are the USLE coefficients.

In the applications of CASC2D-SED, this modified Kilinc and Richardson (1973) equation determines the sediment transport capacity using the following: (1) the overland flow discharge calculated from the model CASC2D; (2) the friction slope calculated from the DEM and water depths; (3) soil erodibility factor from soil texture data; (4) crop-management factor from vegetation and land use data; and (5) the soil conservation practice factor from land use data. The details of this conceptual description are given in the numerical formulation.

NUMERICAL FORMULATION

The raster based model, CASC2D-SED, is a spatially and temporally varying distributive rainfall-runoff model that has been enhanced to erode sediment in the upland areas, route the sediment from the upland areas to the channel system, and route the sediment, through the channel system, to the watershed outlet. CASC2D-SED takes advantage of spatially varying topography (Digital Elevation Maps), soil texture, and land use/ land cover information stored in a Geographical Information System (GIS).

The major features of CASC2D-SED are: (1) Green-Ampt Infiltration routine, (2) two-dimensional diffusive wave overland flow routing, (3) one-dimensional diffusive wave channel flow routing, (4) spatially and temporally varying rainfall, and (5) upland erosion and sediment transport.

The numerical formulation for surface runoff calculations stems from CASC2D (Julien *et al.*, 1995). The algorithm for the continuity equation on elements (j,k) is:

$$h^{t+\Delta t}(j,k) = h^{t}(j,k) + i_e^t \Delta t$$

$$-\left[\frac{q_x^t(k,k+1) - q_x^t(k-1,k)}{W} + \frac{q_y^t(j,j+1) - q_y^t(j-1,j)}{W}\right]\Delta t \tag{4}$$

where $h^{t+\Delta t}(j,k)$ and $h^t(j,k)$ denote flow depths at the element (j,k) at t + Δt and t, respectively; i_e^t is the average excess rainfall rate over one time step beginning from time t; $q_x^t(k,k+1)$ and qxt(k-1,k) describe unit flow rates in the x-direction at time t, from (j,k) to (j,k+1), and from (j,k-1) to (j,k), consecutively; likewise $q_y^t(j,j+1)$, $q_y^t(j-1,j)$ denotes unit flow rates in the y-direction at time t, from (j,k) to (j+1,k), and from (j-1,k) to (j,k), respectively; and W is the square grid size.

The momentum equations in the x and y directions are solved using the diffusive wave approximation. In the x-direction, the friction slope for the diffusive wave approximation is computed as:

$$S_{fx}^t(k-1,k) = S_{ox}(k-1,k) - \frac{h^t(j,k) - h^t(j,k-1)}{W} \tag{5}$$

in which the bed slope is given by:

$$S_{ox}(k-1,k) = \frac{E(j,k) - E(j,k)}{W} \tag{6}$$

where E represents the ground surface elevation of the element.

Therefore the calculated unit discharge q_x^t and unit sediment discharge q_{sx}^t for turbulent flow for $S_{fx}^t(k-1,k) \geq 0$ is given by :

$$q_x^t(k-1,k) = \frac{1}{n(j,k-1)}\left[h^t(j,k-1)\right]^{\frac{5}{3}} |S_{fx}|^{\frac{1}{2}} \tag{7}$$

$$q_{sx}^t(k-1,k) = 25500 q_x^t(k-1,k)^{2.035} |S_{fx}(k-1,k)|^{1.664}$$

$$\frac{K}{0.15}CP \tag{8}$$

where q_x implies unit discharge and q_{sx} implies unit sediment discharge in the x-direction at time t from (j,k-1) to (j,k).

For $S_{fx}^t(k-1,k) < 0$

$$q_x^t(k-1,k) = \frac{-1}{n(j,k)}\left[h^1(j,k)\right]^{\frac{5}{3}} |S_{fx}|^{\frac{1}{2}} \tag{9}$$

$$q_{sx}^t(k-1,k) = 25500 q_x^t(k-1,k)^{2.035} |S_{fx}(k-1,k)|^{1.664}$$

$$\frac{K}{0.15}CP \tag{10}$$

where Equation (9) and Equation (10) correspond to a negative friction slope, negative unit discharge, and negative unit sediment discharge, respectively, thus implying that the flow direction is actually from (j,k) to (j,k-1).

The unit discharge and unit sediment discharge in the y-direction are similarly calculated based on the sign of the friction slope in the y-direction. Figure 1 outlines the upland erosion scheme. Once the direction of flow and the unit sediment discharge have been computed, the upland erosion is separated into three size fractions (sand, silt, and clay). The source of sediment routed downstream includes sediment in suspension, previous deposition, and sediment eroded from the soil surface. Equations (8) and (10) determine the amount of sediment transported from the outgoing cell. To preserve mass balance, the model first gives priority to the volume of sediment in

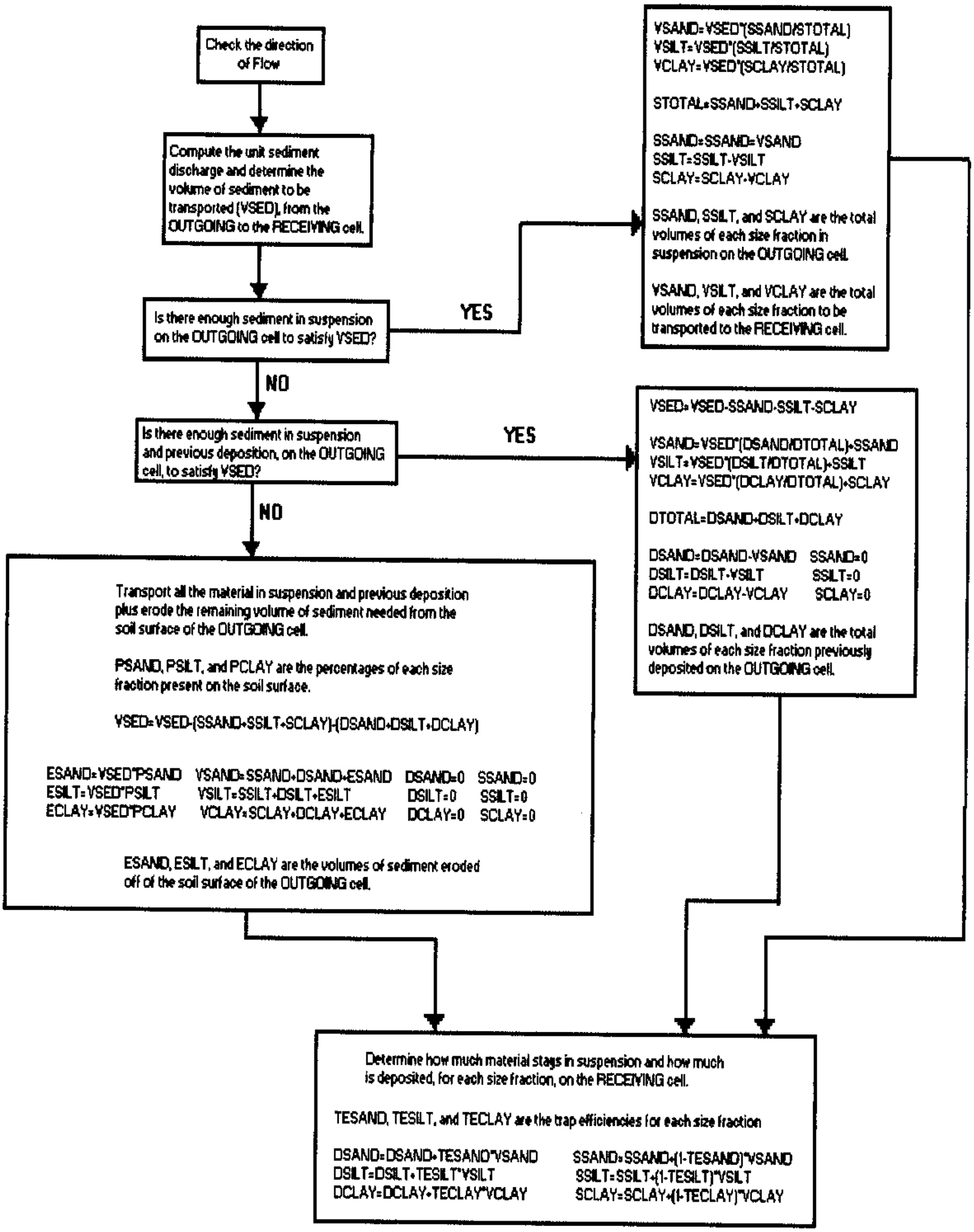


Figure 1. Flow Chart for the Upland Erosion Scheme.

suspension, secondly to the volume of sediment in previous deposition, and lastly the remaining volume of sediment eroded from the soil surface.

In order to determine the quantity of sediment deposited on the receiving cell, the trap efficiency for each size fraction is computed using :

$$T_{E_i} = 1 - e^{\frac{-X\omega_i}{hV}} \tag{11}$$

where T_{Ei} = trap efficiency for each size fraction, X = longitudinal length, ω_i = fall velocity for each size fraction, h = flow depth, and V = flow velocity.

The trap efficiency indicates the quantity of sediment deposited on the receiving cell for each size fraction; thus, the remaining volume of sediment ($1-T_{Ei}$) stays in suspension on the receiving cell.

The model CASC2D-SED routes water and sediment from the upland areas to the watershed outlet. Sediment transport in channels for single storm-events assumes that the change in channel bed elevation and bank erosion processes are small compared to upland erosion processes. The model keeps track of the time changes in the following parameters: rainfall distribution, cumulative infiltration depth, surface runoff depth, suspended sediment volume, sediment flux, and net aggradation/degradation for each pixel. A detailed application example is presented in the next section.

STUDY AREA

The model, CASC2D-SED, was applied to Goodwin Creek, Mississippi, for comparison with field measurements of surface runoff hydrographs and sediment transport graphs at several locations along the watershed. Goodwin Creek (Figure 2) is a tributary of 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 North Mississippi, approximately 60 miles from Memphis, Tennessee, and is extensively gaged by the Agricultural Research Service (ARS) as a research watershed used to study upland erosion, instream sediment transport, and watershed hydrology. The Vicksburg District Corps of Engineers (COE) provided most of the construction funds when this watershed was originally established in 1977 (Blackmarr, 1995).

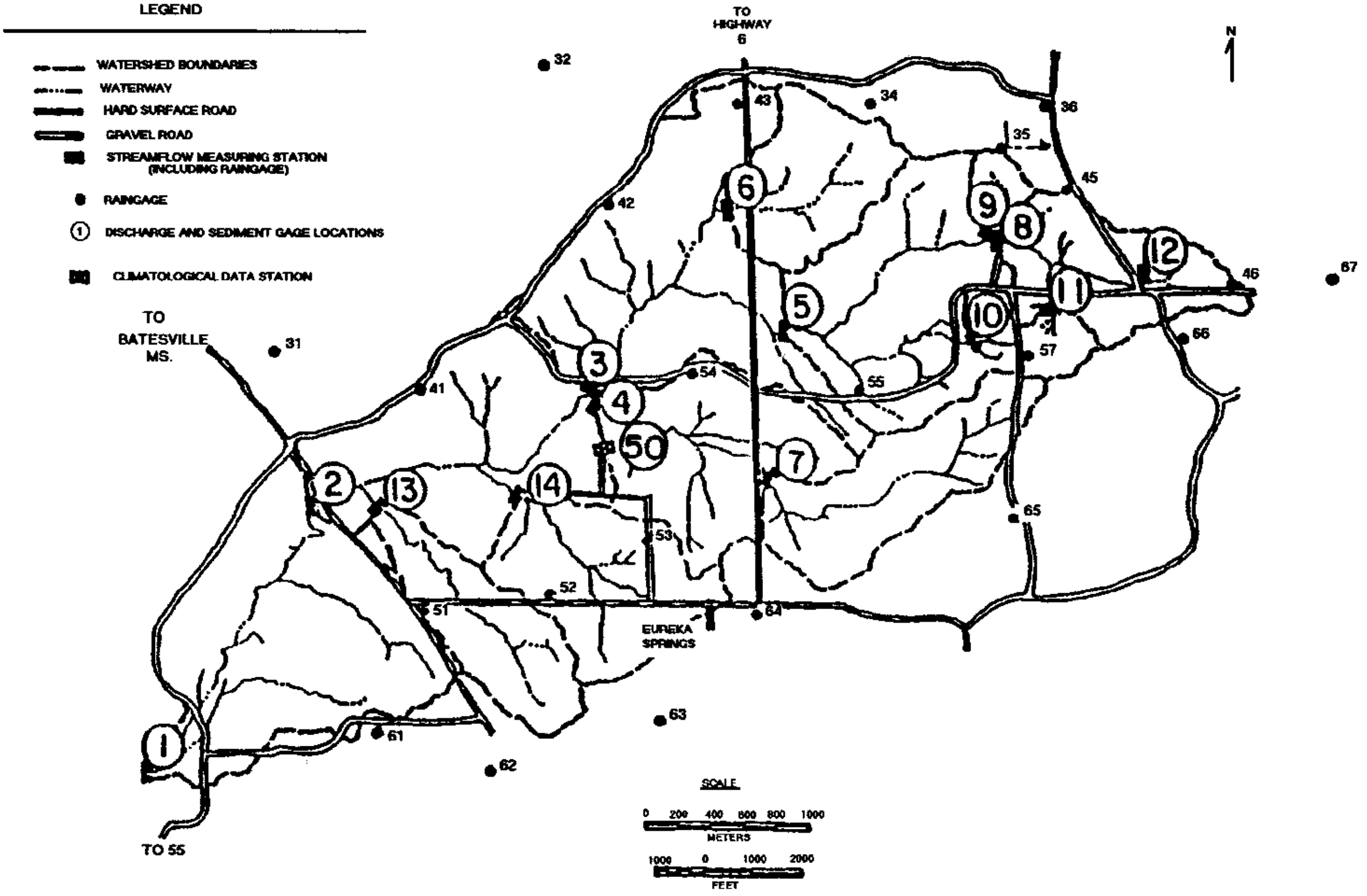


Figure 2. Goodwin Creek Watershed.

The Goodwin Creek watershed is divided into 14 nested subcatchments with a flow measuring flume constructed at each of the drainage outlets. The drainage areas above these stream gaging sites range from 0.63 to 8.26 square miles. Twenty-nine standard recording rain gages are uniformly located within and just outside the watershed.

Instrumentation at each gaging site includes an electronic data acquisition system, which consists of a VHF-radio telemetry system with a microcomputer. This system collects, temporarily stores, and transmits the data at the predetermined intervals to a central computer at the National Sedimentation Laboratory (NSL) in Oxford, Mississippi.

The climate of the watershed is humid, hot in the summer, and mild in the winter. The average annual rainfall during 1982 to 1992 from all storms was 56.7 inches, and the mean annual runoff measured at the watershed outlet was 5.7 inches per year. Data from a standard climatological station near the center of the watershed is also transmitted through the telemetry system. This information complements climatological data available from the U.S. Weather station at Batesville, Mississippi. The scope and quality of data being collected at the Goodwin Creek watershed has recently attracted the attention of scientists from NASA and NOAA working on large scale hydrometerology.

The Goodwin Creek watershed flows approximately from northeast to southwest; it drains a total area of 8.26 square miles, with the outlet at latitude 89°54′50″ and longitude 34°13′55″.

Terrain elevation ranges from 72 meters to 123 meters above mean sea level with an average channel slope of 0.004 in Goodwin Creek. Land use and management practices that influence the rate and amount of sediment delivered to streams from the uplands range from timbered areas to row crops. The Goodwin Creek watershed is largely free of land management activities, with 13 percent of its area being undercultivation and the remainder in idle pasture and forest land. Typical values of overland roughness and cropping management factor C for Goodwin Creek are given in Tables 1 and 2, respectively. The predominant soil texture for Goodwin Creek watershed is silt loam with a small percent of sandy loam. Typical values of the soil erodibility factor K are given in Table 3.

Measurements collected at each site and transmitted through the telemetry system include water stage, accounting of automatically pumped sediment samples, air and water temperature, and precipitation. Manual sampling of total sediment loads is also carried out during storm events at stations 1 and 2 using bedload and depth-integrating suspended samplers. Surveys of channel geometry, bed material, bank geotechnical properties, and channel migration are conducted at periodic intervals to keep track of channel morphological change.

TABLE 1. Overland Roughness Coefficients for Goodwin Creek Watershed.

Land Use	Mannings Roughness Coefficient
Pasture, Idle Land	0.070
Forest	0.110
Row Crop	0.050

TABLE 2. Crop Management Factors (C) for Goodwin Creek Watershed.

Land Use	Crop Management Factor (C)
Pasture, Idle Land	0.070
Forest	0.008
Row Crop	0.650

TABLE 3. Soil Erodibility Factors (K) for Goodwin Creek Watershed.

Soil Texture	Soil Erodibility (K)
Sand	0.12
Sandy-Loam	0.27
Silt-Loam	0.40
Silty-Clay-Loam	0.38

In verifying the model results, a field reconnaissance trip was conducted in November 1996. There was evidence of rill and gully erosion in the lower portion of the Goodwin Creek watershed. In the fields north of the main channel, between gages 2 and 3, the formation of rills and upland sediment deposits were noticed. In this area, sand material from the upland area deposited on the milder sloped fields. As the runoff from the fields neared the main channel, the rills turned into gullies. In the pasture lands located along the watershed boundary, there was evidence of rill and gully formations. In these areas, the ground cover made it somewhat difficult to determine the extent to which rill erosion was taking place; however, gully erosion was very noticeable in most cases.

Along the main stem and tributary channels, there was evidence of bank and bed erosion. The bank angles were very steep in the vicinity of gage 9. There was evidence of block failures and of bank undermining. Around some of the gaging structures, there was evidence of local scour. Along the channel banks of the tributary flowing into gage 9, there was evidence of vegetation being undermined, with trees and shrubs ultimately falling into the channel. The primary land use above gage 9 is pasture; however, the primary sediment supply is from the stream banks and bed. From extensive field observations made by the ARS (Blackmarr, 1995), this area is one of the most active, in terms of gully erosion, within the Goodwin Creek Watershed.

The drainage area above gage 10 consists primarily of forests. This sub-area was established to determine the sediment runoff due to a wooded land use. From field observations, dense vegetation was observed, and there appeared to be very little rill and gully erosion taking place. A search of the Goodwin Creek Database revealed very little sediment runoff measured in the field. The drainage area above gage 11 consists primarily of pasture or idle land. In this area, there was evidence of gully erosion, but not on the same scale as the drainage area above gage 9. The drainage area above gage 12 consists of essentially the same land use as gage 11; however, the channel changes dramatically in size and depth. This would seem to indicate the base lowering of the channel network has not fully reached the upper portion of the watershed. The drainage area above gage 14 consists primarily of pasture and idle land. The primary interest in this sub-area is the character of the channel bed material above the gaging site, which consists primarily of gravel. As a result, the sediment load resulting from this sub-area is expected to be primarily wash load.

From discussions with NSL personnel and review of previous reports (Blackmarr, 1995), the annual sediment yield consists approximately of 30 percent upland erosion and 70 percent bank failure and bed erosion as measured in the main channel of the Goodwin Creek watershed. From field observations made along the main channel, there was strong evidence of gully erosion and bed lowering as well as bank undercutting and block failures taking place.

MODEL APPLICATION AND RESULTS

In evaluating the ability of CASC2D-SED to accurately simulate upland erosion at the watershed scale, three storm events were modeled (Johnson, 1997). In performing this analysis, all GIS data (i.e., DEM, Land Use, and Soil Texture) were resampled to a grid size of 400 square feet. For this paper, only the results from the October 17, 1981, storm event will be presented.

The storm event of October 17, 1981, began at 9:19 p.m. and had a total rainfall duration of 3.5 hours with very little rainfall preceding this event. Total rainfall for this event varied from 2.55 to 3.11 inches with an average value of 2.85 inches (Figure 3, Figure 4). Total runoff varied from 0.87 inches at the upper streamflow gage to 0.64 inches at the downstream gaging location (Figure 5, Figure 6).

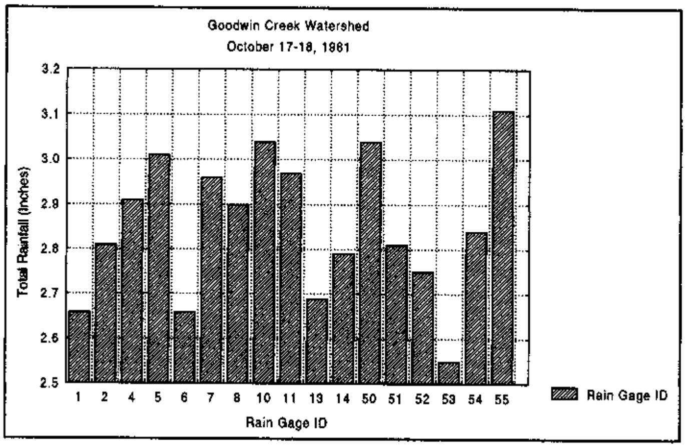


Figure 3. Goodwin Creek Watershed - Total Rainfall (Inches).

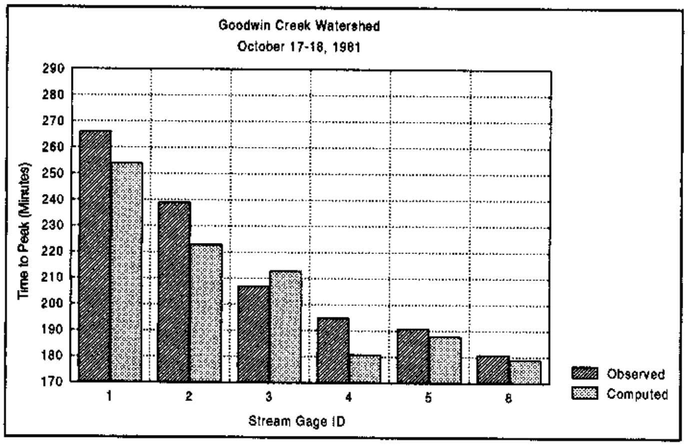


Figure 4. Goodwin Creek Watershed – Time to Peak (Minute).

The maximum overland flow depth was computed to be 0.16 meters, while the maximum channel flow depth was computed to be 2.0 meters. The maximum infiltration depth was computed to be 0.13 meters, and the maximum rainfall intensity for this event was 7.2 inches/hour. The maximum sediment flux generally ranged between 0.0 cm to 0.018 cms; however, there were isolated grid cells where much greater values (2040.0 cm) were computed. The suspended volume of sediment ranged between 0.0 m^3 to 14.8 m^3; however, most of the grid cells showed suspended volume of sediment in the 0.0 m^3 to 0.04 m^3 range. Evaluating the total net volume maps, the maximum sediment deposited on a cell was 1362.2 cubic meters, which results in a deposition depth of 91.6 millimeters (Figure 6). The average volume of sediment deposited, for all the grid cells showing deposition, was 9.5 cubic meters, resulting in an average deposition depth of 0.64 millimeters. The maximum sediment eroded from a grid cell was 1363.1 cubic meters, which results in an erosion depth of 91.7 millimeters (Figure 7). The average volume of sediment eroded, for all the grid cells showing erosion, was 18.3 cubic meters, resulting in an average erosion depth of 1.2 millimeters (Figure 8).

A comparison of the hydrograph plots [Figures 9(a)-9(f)] shows that CASC2D-SED was able to consistently simulate the overall shape and rate of rise. The time to peak was simulated within 3 percent at some places (gage 8 and gage 5), but was off by approximately 15 percent at gages 2 and 4. CASC2D-SED undersimulated the total volume of runoff by approximately 20 percent across the watershed. The peak flows were within 1 percent to 8 percent throughout the watershed, except at gage 3, which was off by 26 percent.

A comparison of the sediment discharge plots [Figures 10(a)-10(i)] shows that CASC2D-SED was able to predict upland erosion off of the Goodwin Creek watershed within an acceptable range of -50 percent to 200 percent of the actual upland erosion. This range (-50 percent to 200 percent) is generally considered by sedimentation engineers to be acceptable when comparing computed sediment yields versus actual sediment yields.

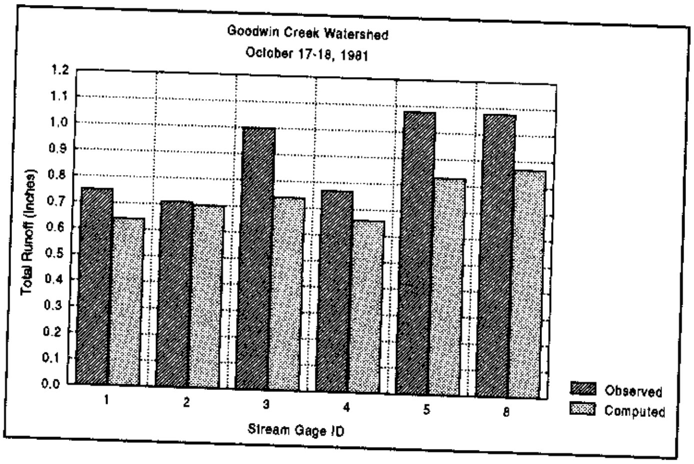


Figure 5. Goodwin Creek Watershed – Total Runoff (Inches).

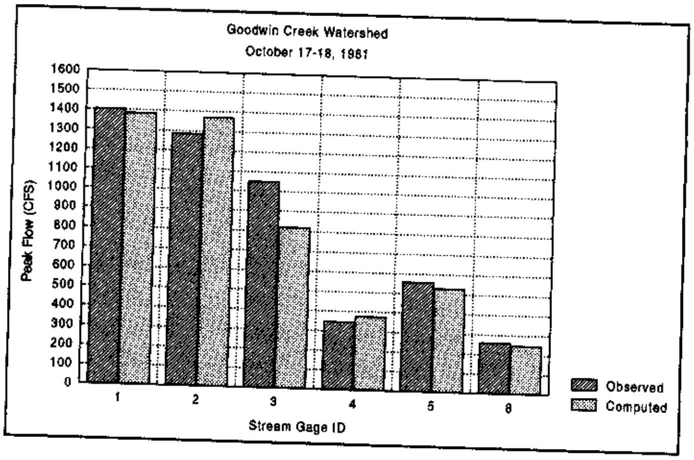


Figure 6. Goodwin Creek Watershed – Peak Flow (CFS).

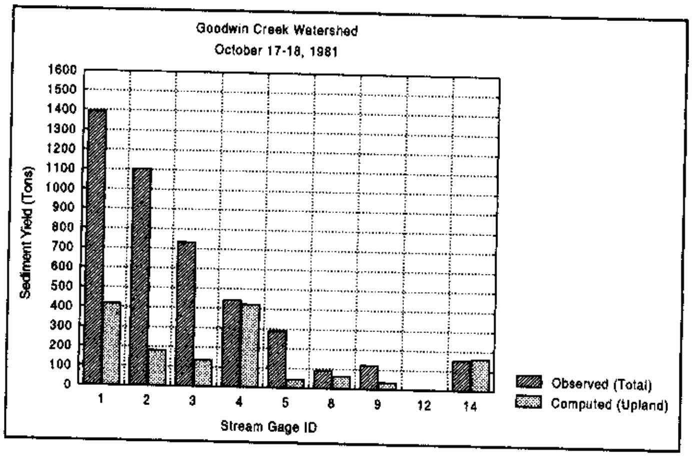


Figure 7. Goodwin Creek Watershed – Sediment Yield (Tons).

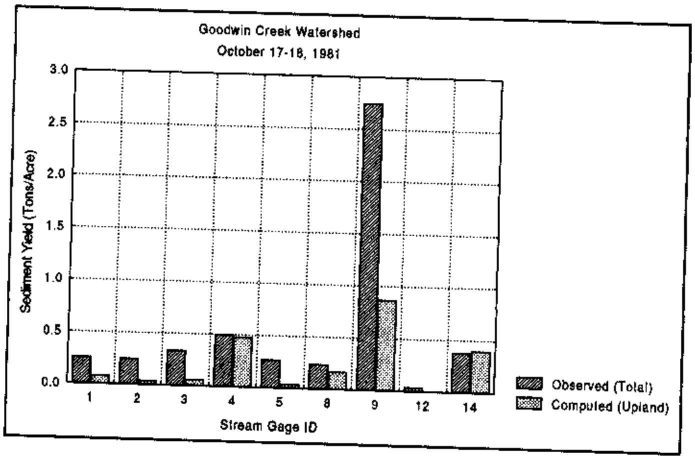
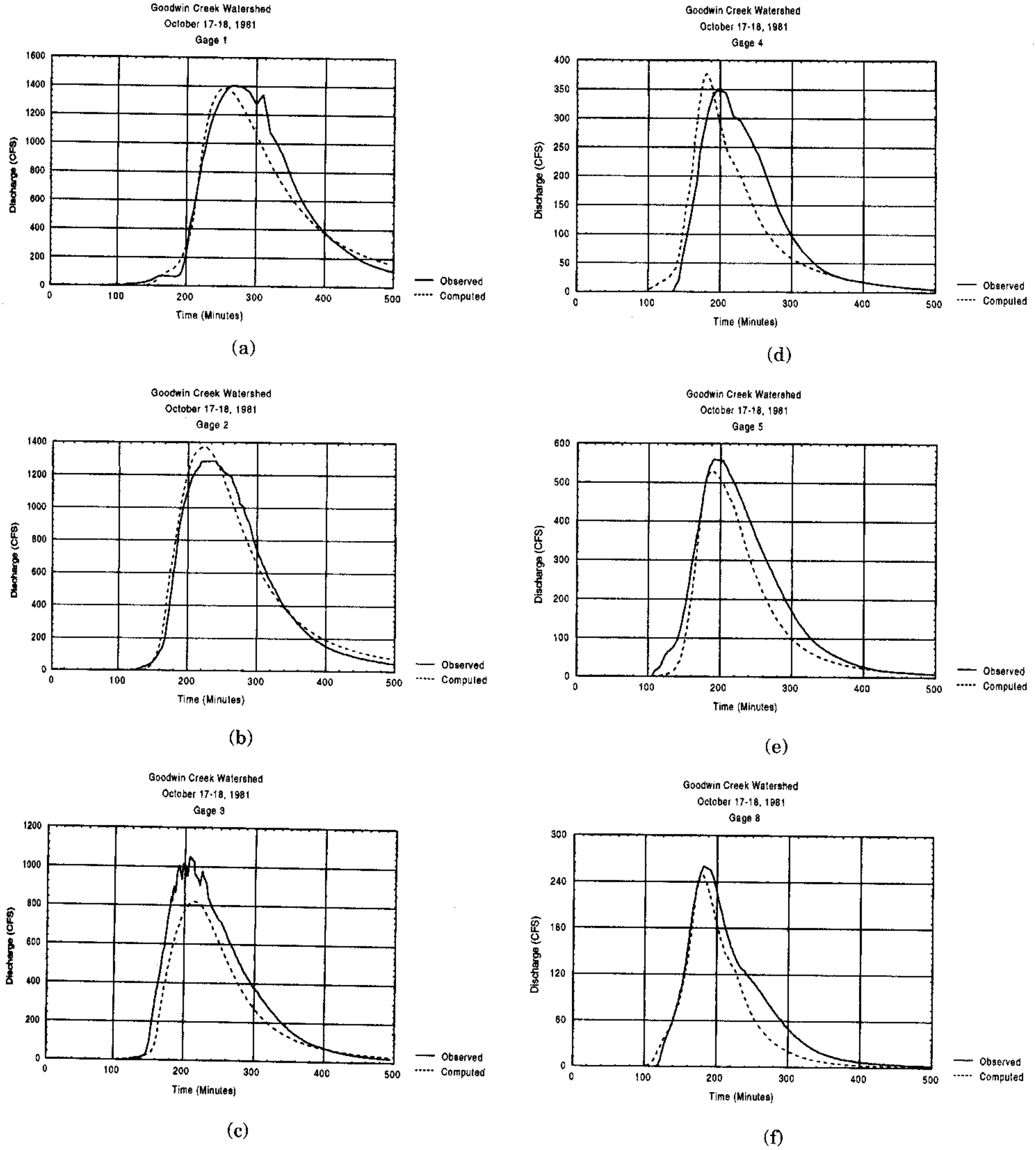


Figure 8. Goodwin Creek Watershed – Sediment Yield (Tons/Acre).



Goodwin Creek Watershed
October 17-18, 1981
Gage 1

(a)

Goodwin Creek Watershed
October 17-18, 1981
Gage 4

(d)

Goodwin Creek Watershed
October 17-18, 1981
Gage 2

(b)

Goodwin Creek Watershed
October 17-18, 1981
Gage 5

(e)

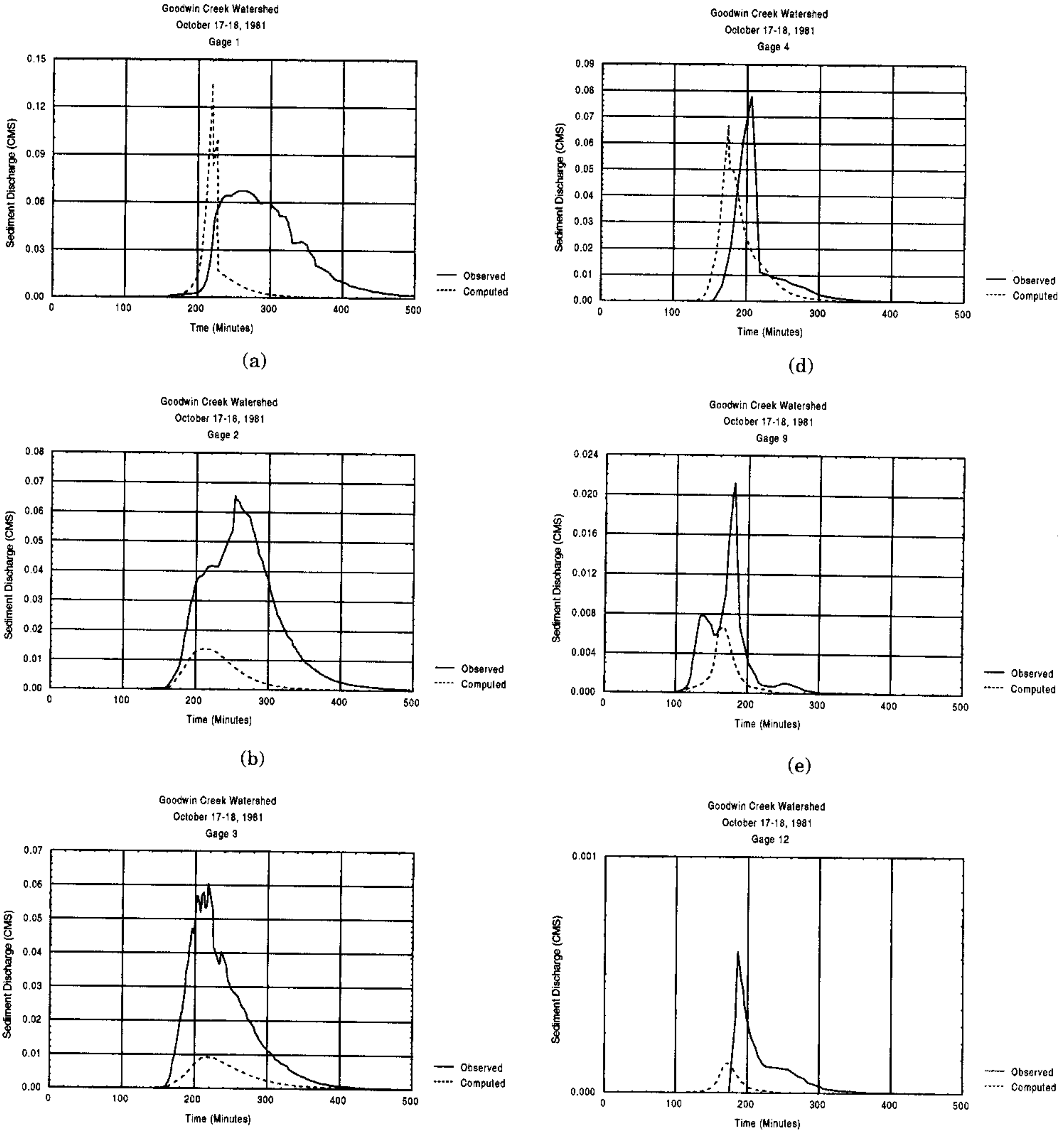
Goodwin Creek Watershed
October 17-18, 1981
Gage 3

(c)

Goodwin Creek Watershed
October 17-18, 1981
Gage 8

(f)

Figure 9. Flow Hydrographs for October 17-18, 1981:
a) Gage 1, (b) Gage 2, (c) Gage 3, (d) Gage 4, (e) Gage 5, (f) Gage 8.



Goodwin Creek Watershed
October 17-18, 1981
Gage 1

(a)

Goodwin Creek Watershed
October 17-18, 1981
Gage 2

(b)

Goodwin Creek Watershed
October 17-18, 1981
Gage 3

(c)

Goodwin Creek Watershed
October 17-18, 1981
Gage 4

(d)

Goodwin Creek Watershed
October 17-18, 1981
Gage 9

(e)

Goodwin Creek Watershed
October 17-18, 1981
Gage 12

(f)

Figure 10. Sediment Discharge Hydrographs for October 17-18, 1981:
a) Gage 1, (b) Gage 2, (c) Gage 3, (d) Gage 4, (e) Gage 5, (f) Gage 8.

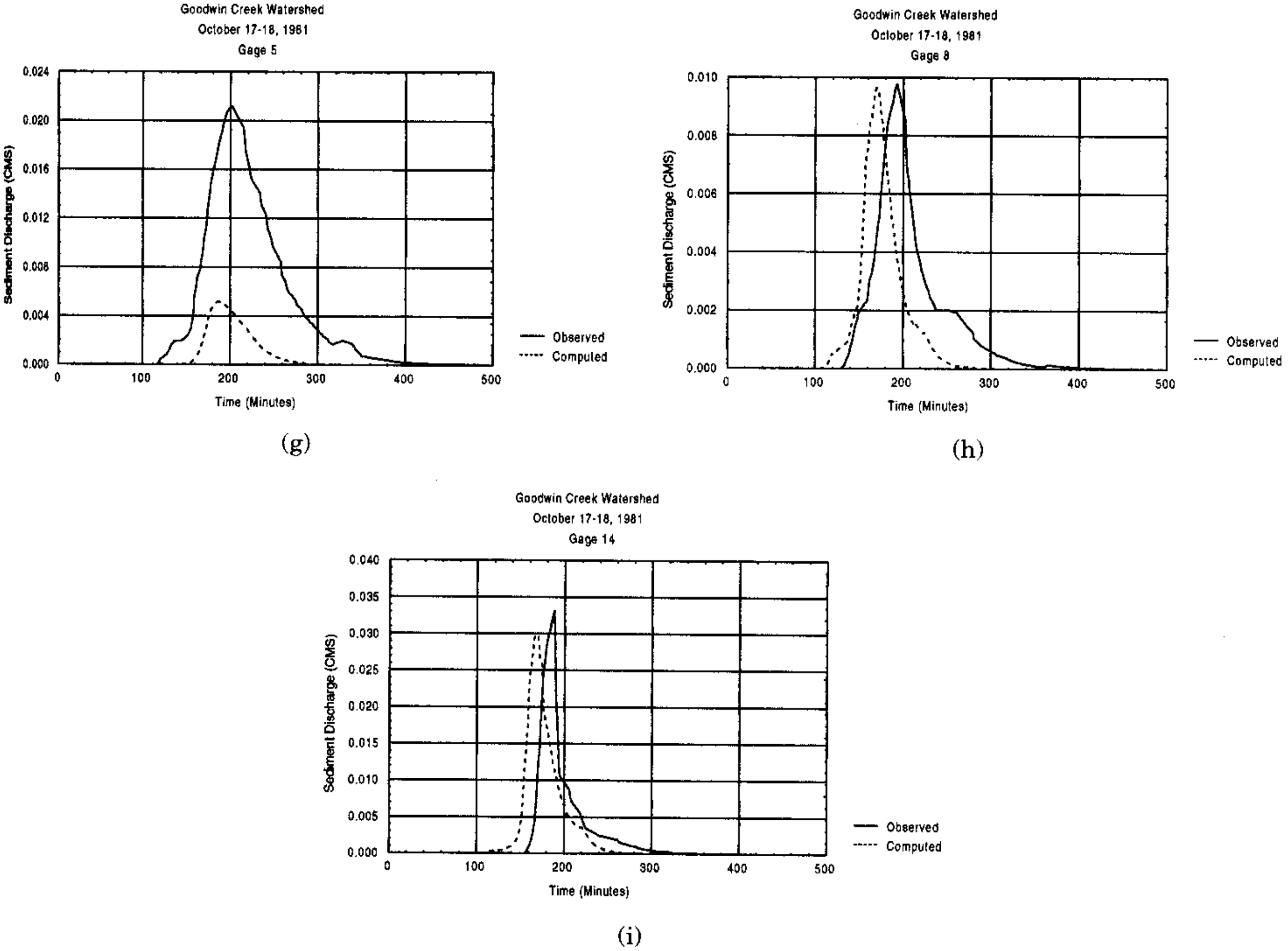


Figure 10. Sediment Discharge Hydrographs for October 17-18, 1981 (cont'd.): (g) Gage 9, (h) Gage 12, (i) Gage 14 (cont'd.).

CONCLUSIONS

From the results of the study discussed in this paper, the computed runoff volume was approximately15 percent lower than the observed runoff volume, across the watershed, and the computed peak flow was between -20 percent to +10 percent across the watershed. The CASC2D-SED upland erosion scheme computed sediment yield within a reasonable limit (-50 percent to 200 percent). The erosion and deposition patterns computed by the upland sediment scheme are reasonable when compared to the field observations made on the Goodwin Creek watershed

LITERATURE CITED

Blackmarr, W. A., 1995. Documentation of Hydrologic, Geomorphic, and Sediment Transport Measurements on the Goodwin Creek Experimental Watershed, North Mississippi, for the Period 1982-1993, Preliminary Release. National Sedimentation Laboratory, Research Report No. 3, October 1995.

Foster, G. R., 1982. NEED NAME OF CHAPTER HERE. *In:* Hydrologic Modeling of Small Watersheds, C. T. Haan, H. P. Johnson, and D. L. Brakensiek (Editors). American Society of Agricultural Engineers, International Standard Book Number 0-916150-44-5, Chapter 8.

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

Julien, P. Y., B. Saghafian, and F. L. Ogden, 1995. Raster-Based Hydrologic Modeling of Spatially-Varied Surface Runoff. Water Resources Bulletin, 31(3):523-536.

Julien, P. Y.,1995. Erosion and Sedimentation. Press Syndicate of the University of Cambridge, New York, New York.

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.

Renard, K. G., et al., 1991. RUSLE – Revised Universal Soil Loss Equation. Journal of Soil and Water Conservation, January-February, pp. 30-33.

Smith, R. E.,1976. Field Test of a Distributed Watershed Erosion/Sedimentation Model, Soil Erosion – Prediction and Control. Soil Conservation Society of America, Ankeny, Iowa, Special Publication 21, pp. 201-209.

NOTATIONS

C	USLE crop management factor.
h	Surface flow depth.
i	Rainfall intensity.
K	USLE soil erodibility factor.
P	USLE conservation practice factor.
q	Unit discharge.
q_s	Unit sediment discharge.
q_x	Unit flow rate in the x-direction.
q_y	Unit flow rate in the y-direction.
S_f	Friction slope.
S_o	Bed slope.
t	Time.
T_{ei}	Trap efficiency for each size fraction.
V	Flow velocity.
x,y	Cartesian spatial coordinates.
X	Longitudinal distance.
ω_i	Fall velocity for each size fraction.
ρ	Mass density of water.
τ_c	Critical shear stress.
τ_o	Applied shear stress.
ν	Kinematic viscosity of water.