The two-dimensional upland erosion model
CASC2D-SED

BILLY E. JOHNSON
Concurrent Technologies Corp. (CTC), 510 Washington Avenue, Bremerton, Washington 98337, USA
e-mail: iohnson@ctc.com

PIERRE Y. JULIEN
Department of Civil Engineering, Engineering Research Center, Colorado State University, Fort Collins, Colorado 80523, USA

Abstract This paper describes the upland erosion algorithm implemented within a two-dimensional rainfall–runoff model (CASC2D-SED) and the application of the model to the Goodwin Creek Watershed, USA.

Key words CASC2D; distributive; Goodwin Creek; hydraulics; hydrology; Kilinc-Richardson; rainfall–runoff; surface runoff; upland erosion; watershed

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 geological agents. In the long term, the effect of erosion is the 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 many effects on the environment including: (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 the land on which it is deposited; (c) carrying chemical and biological pollutants; and (d) the creation of new delta lands.

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.

The analysis of sediment sources aims at estimating the total amount of sediment eroded on the watershed on an annual basis, called “annual gross erosion”. The annual gross erosion $A_T$ depends on the source of sediments 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 (residues from vegetation which help to protect the soil surface from rainfall impact and help to improve the soil structure), residual...
land use, subsurface effects, tillage, roughness, and tillage marks (soil disturbance due to tillage practices) (Foster, 1982).

Modelling soil erosion is the process of mathematically describing soil particle detachment, transport, and deposition on land surfaces. There are at least three reasons for modelling 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 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), developed by Wischmeier & Smith (1978). 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, 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) should be used. 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).

As a result of the limitations and errors discussed above, an increasing number of scientists and engineers are turning to distributed hydrological models. 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 are one class of formal models of real systems in which the governing physical laws are well known and can be described by the equations of mathematical physics. Watershed runoff can be generated by several mechanisms, all of which can be described by the theory of unsaturated or saturated porous media flow. The equations of continuity and momentum provide a physically based model for unsteady free surface flow, and the diffusive approximation is usually appropriate for overland flow. Therefore, the development of detailed physically based models of the erosion–sedimentation process, which incorporate the talents of diverse interests such as engineering, hydrology, and agronomy, will lead to improved understanding of the mechanics of soil detachment, transport, and deposition (Foster, 1982).

The objective of this paper is to develop an upland erosion subroutine for the two-dimensional (2-D) surface runoff model CASC2D. The algorithm is to be tested with field measurements at several sediment gauging stations on Goodwin Creek, USA.

SURFACE HYDROLOGY

Surface hydrology consists of those processes that describe the distribution of rainfall, infiltration of rainfall into the ground, and the routing of excess rainfall across the overland planes into channels and ultimately to the watershed outlet. The 2-D surface runoff model CASC2D, developed by Julien & Saghafian (1991), is used to calculate surface flow depth, unit discharge, and friction slope.
Spatial rainfall distribution

When analysing rainfall data from rain gauges, an interpolation scheme based on the inverse distance squared approximates the distribution of rainfall intensity over the watershed (Julien & Saghafian, 1995).

Infiltration

The Green-Ampt infiltration scheme has gained considerable attention due to the ever growing trend towards physically based hydrological modelling (Philip, 1983). The parameters of the Green-Ampt equation are based on the physical characteristics of the soil and therefore can be determined by field measurements or experiments. The Green-Ampt equation may be written as (Philip, 1983):

\[ f = K_s \left( 1 + \frac{H_f M_d}{F} \right) \]

where:
- \( f \) infiltration rate (cm h\(^{-1}\))
- \( K_s \) hydraulic conductivity at normal saturation (cm h\(^{-1}\))
- \( H_f \) capillary pressure head at the wetting front (cm)
- \( M_d \) soil moisture deficit equal to \((\theta_c - \theta_i)\)
- \( \theta_c \) effective porosity equal to \((\phi - \theta_r)\)
- \( \phi \) total soil porosity
- \( \theta_r \) residual saturation
- \( \theta_i \) initial soil moisture content
- \( F \) total infiltration depth (cm)

The head due to surface depth has been neglected as \( H_f \) easily overpowers shallow overland depth.

Overland flow

The Saint-Venant equations of continuity and momentum describe the mechanics of overland flow. The 2-D continuity equation in partial differential form reads as:

\[ \frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = i_e \]

where:
- \( h \) surface flow depth (m)
- \( q_x \) unit flow rate in the x-direction (m\(^2\) s\(^{-1}\))
- \( q_y \) unit flow rate in the y-direction (m\(^2\) s\(^{-1}\))
- \( i_e \) excess rainfall intensity equal to \((i - f)\) (m s\(^{-1}\))
- \( i \) rainfall intensity (m s\(^{-1}\))
- \( f \) infiltration rate (m s\(^{-1}\))
- \( x, y \) cartesian spatial coordinates (m)
- \( t \) time (s)
The momentum equation in the $x$ and $y$ direction may be derived by equating the net forces per unit mass in each direction to the acceleration of flow in the same direction.

The diffusive wave formulation of the equations of motion are:

$$S_{f_k} = S_{ax} - \frac{\partial h}{\partial x}$$  \hspace{1cm} (3)

From the three equations of continuity and momentum, five hydraulic variables need to be determined. Therefore, a resistance law should be established to relate flow rate to depth and to other parameters. A general depth–discharge relationship, from the Manning’s resistance equation, is written as:

$$q_x = \frac{S_{f_k}^{1/2} h^{3/2}}{n}$$  \hspace{1cm} (4)

where $n$ = Manning’s roughness coefficient.

**Channel flow**

The governing equations, for channel flow, are similar to those of overland flow except for a finite channel width and for one-dimensional flow. The equation of continuity reads as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l$$  \hspace{1cm} (5)

where:
- $A$ = channel flow cross section ($m^2$)
- $Q$ = total discharge in the channel ($m^3 s^{-1}$)
- $q_l$ = lateral inflow rate per unit length, into or out of the channel ($m^2 s^{-1}$)

Most cases of channel flow occur in the turbulent flow regime. The following equation represents the application of Manning’s resistance equation to channel flow:

$$Q = \frac{1}{n} AR^{2/3} S_f^{1/2}$$  \hspace{1cm} (6)

where:
- $R$ = hydraulic radius (m)
- $S_f$ = friction slope (m m$^{-1}$)

**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 erosion under simulated rainfall can be assumed to be related to a number of different variables. Therefore, sediment transport is related to the following variables:
where:

- $q_s$: unit sediment discharge ($m^2 s^{-1}$)
- $S_o$: bed slope ($m m^{-1}$)
- $q$: unit discharge ($m^2 s^{-1}$)
- $i$: rainfall intensity ($m s^{-1}$)
- $X$: longitudinal distance (m)
- $\rho$: mass density of water (kg m$^{-3}$)
- $v$: kinematic viscosity of water ($m^2 s^{-1}$)
- $\tau_c$: critical shear stress (N m$^{-2}$)
- $\tau_a$: applied shear stress (N m$^{-2}$)

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

$$q_s = 25500q_o^{2.035}S_o^{1.664}$$

where $q_s$ is in the units of (tons m$^{-1}$ x s).

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

$$q_s = 25500q_o^{2.035}S_o^{1.664} \frac{K}{0.15} CP$$

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

This modified Kilinc & Richardson equation determines the sediment transport capacity from one overland grid cell to the next for three size fractions (i.e. sand, silt, and clay). In order to determine how much sediment stays in suspension or is deposited on the receiving cell, for each size fraction the sediment transported out of a grid cell will first be assumed to come from sediment already in suspension, second from previously deposited sediment, and lastly from the soil surface (Figs 1(a,b)). The details of this conceptual description are given in the numerical formulation.

**NUMERICAL FORMULATION**

The numerical formulation for surface runoff calculations stems from CASC2D (Julien & Saghafian, 1991). The algorithm for the continuity equation on elements $(j,k)$ is:

$$h'^{i+1}(j,k) = h'^i(j,k) + i_e \Delta t -$$

$$\left[ \frac{q'_x(j \rightarrow k + 1) - q'_x(j \rightarrow k - 1)}{W} + \frac{q'_x(j - 1 \rightarrow j) - q'_x(j \rightarrow j + 1)}{W} \right] \Delta t$$

where $h'^{i+1}(j,k)$ and $h'(j,k)$ denote flow depths at the element $(j,k)$ at $t + \Delta t$ and $t$, respectively; $i_e$ is the average excess rainfall rate over one time step beginning from time $t$; $q'_x(j \rightarrow k + 1)$ and $q'_x(j \rightarrow k - 1)$ describe unit flow rates in the x-direction at
Check the Direction of Flow and determine the volume of sediment to be transported (VSED), from the Outgoing to the Receiving cell.

Is there enough sediment in suspension on the Outgoing cell to satisfy VSED? Yes/No

Is there enough sediment in suspension and previous deposition, on the Outgoing cell to satisfy VSED? Yes/No

Transport all the material in suspension and previous deposition plus erode and remaining volume of sediment needed from the soil surface of the Outgoing cell.

PSAND, PSILT, and PCLAY are the percentages of each size fraction present on the soil surface.

\[
VSED = VSED \times (SSAND/STOTAL) \\
VSED = VSED \times (SSILT/STOTAL) \\
VSED = VSED \times (SCLAY/STOTAL) \\
STOTAL = SSAND + SSILT + SCLAY \\
SSAND = SSAND \times VSAND \\
SSILT = SSILT \times VSILT \\
SCLAY = SCLAY \times VCLAY
\]

VSED + VSAND - (SSAND+SSILT+SCLAY) \times (DSAND+DSILT+DCLAY)

ESAND = VSED \times PSAND \\
ESILT = VSED \times PSILT \\
ECLAY = VSED \times PCLAY

ESAND, ESILT, and ECLAY are the volumes of sediment eroded

Determine how much material stays in suspension and how much is deposited, for each size fraction, on the Receiving cell.

TESAND, TESILT, and TECLAY are the trap efficiencies for each size fraction.

\[
DSAND = DSAND + TESAND \times VSAND \quad SSAND = SSAND \times (1-TESAND) \times VSAND \\
DSILT = DSILT + TESILT \times VSILT \quad SSILT = SSILT \times (1-TESILT) \times VSILT \\
DCLAY = DCLAY + TECLAY \times VCLAY \quad SCLAY = SCLAY \times (1-TECLAY) \times VCLAY
\]

Fig. 1 Flowchart for the upland erosion scheme.
time $t$, from $(j,k)$ to $(j, k + 1)$, and from $(j,k)$ to $(j,k - 1)$ consecutively; likewise $q_y(j \to j + 1), q_y(j - 1 \to j)$ 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 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:

$$S'_{fr}(k - 1 \to k) = S_{av}(k - 1 \to k) - \frac{h'(j,k) - h'(j,k - 1)}{W}$$

where $W$ is the grid size.

$$S_{av}(k - 1 \to k) = \frac{E(j,k) - E(j,k)}{W}$$

in which the bed slope is given by:

The calculated unit discharge $q'_x$ and unit sediment discharge $q'_{sx}$ for turbulent flow is given by:

For $S'_{fr}(k - 1 \to k) > 0$

$$q'_x(k - 1 \to k) = \frac{1}{n(j,k)} [h'(j,k - 1)]^{\frac{5}{2}}$$

For $S'_{fr}(k - 1 \to k) < 0$

$$q'_x(k - 1 \to k) = -\frac{1}{n(j,k)} [h'(j,k)]^{\frac{5}{2}}$$
where equation (15) and equation (16) 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. Once the direction of flow and the unit sediment discharge have been computed, the upland erosion is broken down into three size fractions (sand, silt, and clay) and routed based upon how much sediment is in suspension, previous deposition, and how much sediment has been eroded from the soil surface (Fig. 3). In determining how much sediment is transported from the outing cell, the model first gives priority to the volume of sediment in suspension, secondly to the volume of sediment in previous deposition, and lastly the remaining volume of sediment, is eroded from the soil surface. In order to determine how much sediment stays in suspension and how much is deposited on the receiving cell, the trap efficiency for each size fraction is computed using:

\[
T_{ei} = 1 - e^{-\frac{-X_{ei}}{hV}}
\]  

(17)

where:

- \(T_{ei}\) trap efficiency for each size fraction
- \(X\) longitudinal length (m)
- \(\omega\) fall velocity for each size fraction (m s\(^{-1}\))
- \(h\) flow depth (m)
- \(V\) flow velocity (m s\(^{-1}\))

The trap efficiency indicates how much sediment deposits on the receiving cell for each size fraction, thus the remaining volume of sediment \((1 - T_{ei})\) stays in suspension on the receiving cell.

**Fig. 3** Schematic of upland erosion scheme.
The two-dimensional upland erosion 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 (Johnson, 1997). A detailed application example is presented below.

**STUDY AREA**

The model CASC2D-SED has been applied to Goodwin Creek, Mississippi (Johnson, 1997), for comparison with field measurements of surface runoff hydrographs and sediment transport graphs at several locations along the watershed. Goodwin Creek (Fig. 4) 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 96 km (60 miles) from Memphis, Tennessee, and is extensively gauged by the Agricultural Research Service (ARS) as a research watershed for study of upland erosion, instream sediment transport, and watershed hydrology. The Vicksburg COE provided most of the construction funds when this watershed was originally established in 1977 (Blackmarr, 1995).

---

Streams
Watershed Boundary
Roads

Fig. 4 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 streamgauging sites range from 1.61 to 21.15 km$^2$ (0.63–8.26 square miles). Twenty-nine standard recording raingauges are uniformly located within and just outside the watershed.
Instrumentation at each gauging 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).

The climate of the watershed is humid, hot in the summer and mild in the winter. The average annual rainfall during 1982–1992 from all storms was 1361 mm (56.7 inches), and the mean annual runoff measured at the watershed outlet was 137 mm (5.7 inches per year). Data from a standard climatological station near the centre of the watershed is also transmitted through the telemetry system. This information complements climatological data available from the US 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 hydrometeorology.

The watershed flows approximately from northeast to southwest, it drains a total area of 21.15 km$^2$ (8.26 square miles), with the outlet at W89°54′50″ and N34°13′55″. Terrain elevation ranges from 72 m to 123 m a.m.s.l. (Fig. 5) 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, 13% of its area being under cultivation and the rest in idle pasture and forest land (Fig. 6). Typical values of overland roughness and cropping management factor $C$ for Goodwin Creek are given in Table 1. Periodic acquisition of aerial photography and satellite data contribute to complete aerial coverage of land use and surface conditions. The predominant soil texture for Goodwin Creek watershed is silt loam with a small percent of sandy loam (Fig. 7). Typical values of the soil erodibility factor $K$ are given in Table 2.

<table>
<thead>
<tr>
<th>Land use</th>
<th>Manning’s roughness coefficient</th>
<th>Crop management factor ($C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture, idle land</td>
<td>0.070</td>
<td>0.070</td>
</tr>
<tr>
<td>Forest</td>
<td>0.110</td>
<td>0.008</td>
</tr>
<tr>
<td>Row crop</td>
<td>0.050</td>
<td>0.650</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Soil erodibility ($K$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.12</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.27</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.40</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.38</td>
</tr>
</tbody>
</table>

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 load is also carried out during storm events at stations 1 and 2 using bed load and depth-integrating suspended samplers. Surveys of channel geometry, bed material, bank geotechnical properties, and channel migration were conducted at intervals to keep track of channel morphology change.
Fig. 5 Goodwin Creek watershed elevation grid.

Fig. 6 Goodwin Creek watershed land use grid.

Fig. 7 Goodwin Creek watershed soil texture grid.
MODEL APPLICATION

In evaluating the ability of CASC2D-SED to simulate upland erosion accurately at the watershed scale, three storm events were modelled. The first storm event occurred on 17–18 October 1981 and had a storm duration of 8 h; the second on 2–3 December 1983, storm duration 30 h; and the third on 2–3 May 1984, storm duration 28 h. In choosing these three storm events, the goal was to select storms that occurred at different times of the year, but were grouped close enough together such that there would not be a significant change in the land use management practices other than due to agricultural practices.

A total of 17 raingauges were used for the calculations. Simulated streamflow hydrographs were compared to observed hydrographs at five locations on the main stem channel and one major tributary. Simulated sediment discharge graphs were compared to observed sediment graphs at eleven locations along the main stem, tributaries, and upland areas. For all of the input maps (i.e. elevation, land use, and soil texture) the grid cell resolution was set to be 400 feet (121.6 m) in height and 400 feet in width. In computing the output maps, the same grid cell resolution was used. The land use map is broken down into three categories: pasture, crop, and forest. The soil texture map includes four soil textures: silty clay loam, silt loam, clay loam, and sand.

Streamflow, rainfall, and sediment gauge data for Goodwin Creek watershed were available from 1981 to 1993. Total rainfall in inches for the three selected storms are shown in Table 3 for all 17 rainfall gauges.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.66</td>
<td>5.83</td>
<td>4.65</td>
</tr>
<tr>
<td>2</td>
<td>2.81</td>
<td>5.89</td>
<td>4.46</td>
</tr>
<tr>
<td>4</td>
<td>2.91</td>
<td>5.79</td>
<td>4.62</td>
</tr>
<tr>
<td>5</td>
<td>3.01</td>
<td>5.72</td>
<td>4.51</td>
</tr>
<tr>
<td>6</td>
<td>2.66</td>
<td>5.83</td>
<td>4.48</td>
</tr>
<tr>
<td>7</td>
<td>2.96</td>
<td>5.68</td>
<td>4.50</td>
</tr>
<tr>
<td>8</td>
<td>2.90</td>
<td>5.87</td>
<td>4.89</td>
</tr>
<tr>
<td>10</td>
<td>3.04</td>
<td>5.85</td>
<td>4.64</td>
</tr>
<tr>
<td>11</td>
<td>2.97</td>
<td>5.73</td>
<td>4.64</td>
</tr>
<tr>
<td>13</td>
<td>2.69</td>
<td>6.00</td>
<td>4.59</td>
</tr>
<tr>
<td>14</td>
<td>2.79</td>
<td>5.81</td>
<td>4.64</td>
</tr>
<tr>
<td>50</td>
<td>3.04</td>
<td>5.80</td>
<td>4.90</td>
</tr>
<tr>
<td>51</td>
<td>2.81</td>
<td>5.93</td>
<td>4.73</td>
</tr>
<tr>
<td>52</td>
<td>2.75</td>
<td>5.88</td>
<td>4.78</td>
</tr>
<tr>
<td>53</td>
<td>2.55</td>
<td>5.86</td>
<td>4.69</td>
</tr>
<tr>
<td>54</td>
<td>2.84</td>
<td>5.83</td>
<td>4.76</td>
</tr>
<tr>
<td>55</td>
<td>3.11</td>
<td>5.64</td>
<td>4.64</td>
</tr>
<tr>
<td>Average</td>
<td>2.85</td>
<td>5.82</td>
<td>4.65</td>
</tr>
</tbody>
</table>

Simulated results for each of the selected storms are included below. Storm event 1 was used to calibrate the roughness and USLE coefficients. Storm events 2 and 3 were used to verify that the coefficients were accurately simulating flow and sediment discharge within acceptable ranges at the watershed outlet and at various points within
The two-dimensional upland erosion model CASC2D-SED

the watershed. In verifying storm events 2 and 3, only the infiltration parameters were adjusted to take into account the antecedent moisture conditions.

Storm event 1

The storm event of 17 October 1981 began at 21:19 h and had a total rainfall duration of 3.5 h with very little rainfall preceding this event. Total rainfall for this event varied from 2.55 inches (64.8 mm) to 3.11 inches (79.0 mm) with an average value of 2.85 inches (72.4 mm). The time to peak varied from 179 min, at gauge 8, to 254 min at gauge 1 (Table 4). Total runoff varied from 0.87 inches (22.1 mm), at gauge 8, to 0.64 inches (16.3 mm), at gauge 1 (Table 5). The peak discharge varied from 248.7 cfs (cubic feet per second) (7.0 m³ s⁻¹), at gauge 8, to 1385.3 cfs (39.3 m³ s⁻¹), at gauge 1 (Table 6).

Table 4 Goodwin Creek watershed: time to peak (min).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>266</td>
<td>254</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>239</td>
<td>223</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>207</td>
<td>213</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>195</td>
<td>181</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>191</td>
<td>188</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>181</td>
<td>179</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5 Goodwin Creek watershed: total runoff (inches).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>0.64</td>
<td>-14.7</td>
</tr>
<tr>
<td>2</td>
<td>0.71</td>
<td>0.70</td>
<td>-1.4</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.74</td>
<td>-26.0</td>
</tr>
<tr>
<td>4</td>
<td>0.77</td>
<td>0.66</td>
<td>-14.3</td>
</tr>
<tr>
<td>5</td>
<td>1.08</td>
<td>0.83</td>
<td>-23.1</td>
</tr>
<tr>
<td>8</td>
<td>1.08</td>
<td>0.87</td>
<td>-19.4</td>
</tr>
</tbody>
</table>

Table 6 Goodwin Creek watershed: peak flow (cubic feet per second).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1405.1</td>
<td>1385.3</td>
<td>-1.4</td>
</tr>
<tr>
<td>2</td>
<td>1286.5</td>
<td>1372.0</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>1050.6</td>
<td>820.1</td>
<td>-21.9</td>
</tr>
<tr>
<td>4</td>
<td>347.2</td>
<td>376.4</td>
<td>8.4</td>
</tr>
<tr>
<td>5</td>
<td>560.3</td>
<td>529.1</td>
<td>-5.6</td>
</tr>
<tr>
<td>8</td>
<td>260.2</td>
<td>248.7</td>
<td>-4.4</td>
</tr>
</tbody>
</table>

The CASC2D-SED output grids show various grids (i.e. rainfall, infiltration, depth, sediment flux, suspended sediment volume, and total net volume) changing with time for this simulation. The maximum overland depth was computed to be 0.16 m while the maximum channel depth was computed to be 2.0 m. The maximum
infiltration depth was computed to be 0.13 m and the maximum rainfall intensity for this event was 7.2 inches per hour (182.9 mm h⁻¹). Evaluating the total net volume maps, the maximum sediment deposited on a cell was 1362.2 m³, which results in a deposition depth of 91.6 mm. The average volume of sediment deposited, for all the grid cells showing deposition, was 9.5 m³, resulting in an average deposition depth of 0.64 mm. The maximum sediment eroded from a grid cell was 1363.1 m³, which results in an erosion depth of 91.7 mm. The average volume of sediment eroded, for all the grid cells showing erosion, was 18.3 m³, resulting in an average erosion depth of 1.2 mm.

A comparison of the hydrograph plots (Fig. 8) show that CASC2D-SED was able to consistently simulate the overall shape and rate of rise. The time to peak was simulated within 3% at some places (gauge 8 and gauge 5), but was off by approximately 15% at gauges 2 and 4. CASC2D-SED simulated the total volume of runoff low by approximately 20% across the watershed. The peak flows were within 1% to 8% throughout the watershed except at gauge 3, which was off by 26%.

A comparison of the sediment discharge plots (Fig. 9) show that CASC2D-SED was able to predict upland erosion off of the Goodwin Creek watershed within an acceptable range of -50% to 200% of the actual upland erosion. This range (-50% to 200%) is generally considered by sedimentation engineers to be acceptable when comparing computed sediment yields versus actual sediment yields.

**Storm event 2**

The storm event of 2 December 1983 began at 12:00 h and had a total rainfall duration of 30 h. There was significant rainfall preceding this event, therefore infiltration rates can be expected to be low. Total rainfall varied from 5.64 inches (143.3 mm) to 6.00 inches (152.4 mm) with an average of 5.82 inches (147.8 mm). The time to peak varied from 2080 min, at gauge 8, to 2092 min, at gauge 1 (Table 4). Total runoff varied from 4.88 inches (124.0 mm), at gauge 8, to 4.85 inches (123.2 mm), at gauge 1 (Table 5). The peak discharge varied from 304.6 cfs (8.6 m³ s⁻¹), at gauge 8, to 3347.8 cfs (94.9 m³ s⁻¹), at gauge 1 (Table 6).

The maximum overland depth was computed to be 1.1 m and the maximum channel depth was computed to be 3.1 m. The maximum infiltration depth was computed to be 0.2 m with the maximum rainfall intensity being 10.8 inches/hour. Evaluating the total net volume maps, the maximum sediment deposited on a grid cell was 4816.7 m³, which results in a sediment deposition depth of 323.9 mm.

The average volume of sediment deposited, over the grid cells showing deposition, was 76.9 m³, resulting in an average deposition depth of 5.2 mm. The maximum sediment eroded off of a grid cell was computed to be 4612.1 m³, which results in an erosion depth of 310.1 mm. The average volume of sediment eroded, over the grid cells showing erosion, was 42.2 m³, resulting in an average erosion depth of 2.8 mm.

**Storm event 3**

The storm event of 2–3 May 1984 began at 12:00 h and had a total rainfall duration of 28 h. There was a moderate amount of rainfall preceding this event, therefore the
Fig. 8 Flow hydrographs for 17–18 October 1981.
Fig. 9: Sediment discharge hydrographs for 17-18 October 1981.
infiltration rates can be expected to be low in some areas. Total rainfall for this event varied from 4.46 inches (113.3 mm) to 4.90 inches (124.5 mm) with an average value of 4.65 inches (118.1 mm). The time to peak varied from 1372 min, at gauge 8, to 1420 min, at gauge 1 (Table 4). Total runoff varied from 3.76 inches (95.5 mm) at gauge 8 to 3.66 inches (93.0 mm) at gauge 1. The peak discharge varied from 535.2 cfs (15.2 m³ s⁻¹), at gauge 8, to 3743.5 cfs (106.1 m³ s⁻¹), at gauge 1 (Table 6).

The maximum overland depth was computed to be 0.9 m with the maximum channel depth being computed to be 3.5 m. The maximum infiltration depth was computed to be 0.13 m and the maximum rainfall intensity was 15.6 inches per hour. Evaluating the total net volume maps, the maximum sediment deposited on a grid cell was computed to be 6054.7 m³, resulting in a deposition depth of 407.1 mm. The average volume of sediment deposited, over all the grid cells showing deposition, was 109.8 m³, resulting in an average deposition depth of 7.4 mm. The maximum volume of sediment eroded off of a grid cell was 6058.0 m³, which results in an erosion depth of 407.3 mm. The average volume of sediment eroded, over all the grid cells showing erosion, was 62.7 m³, resulting in an average erosion depth of 4.2 mm.

Streamflow hydrograph parameters considered for comparison purposes includes time to peak in minutes (Table 4), total runoff in inches (Table 5), and peak flow in cfs (Table 6). Sediment yield parameters considered for calibration and comparison purposes include sediment yield in tons (Table 7) and sediment yield in tons per acre (Table 8). It should be noted that the observed sediment yield includes upland erosion, bank failure, and channel erosion processes, while the computed sediment yield only consists of upland erosion processes.

From evaluating the total net volume maps, for storm event 1, as the overland flow moves towards the crop lands, between gauges 2 and 3, some of the eroded material starts to deposit. Comparing the total sediment yield (tons) vs upland erosion (tons) (Table 7) and the total sediment yield (tons/acre) vs upland erosion (tons/acre) (Table 8), one can see that the percentage of upland erosion as a component of total sediment yield is within acceptable ranges (20% to 40%) for the Goodwin Creek watershed. From field observations and data collection activities over a number of years (1981–1997), the ARS has estimated the contribution of upland erosion to the total sediment yield, at the outlet of the Goodwin Creek watershed, to be 20% to 40%. The total sediment yield at the outlet was 1394.4 tons and 0.26 tons/acre while CASC2D-SED computed upland erosion, at the outlet, to be 420.6 tons and 0.08 tons/acre. This resulted in the volume of sediment passing the outlet due to upland erosion being 30.2% of the total volume of sediment. For this simulation, gauges 4 and 14 showed the highest percentage of upland erosion at 95.3% and 106.5%, with gauge 5 showing the lowest at 15.6%.

A comparison of the hydrograph parameters, for storm event 2 (Tables 4 to 6) shows that CASC2D-SED was able to simulate the overall shape and rate of rise. However, this simulation produced time to peaks consistently too fast (12 min to 36 min) when compared to observed time to peaks throughout the watershed.

A comparison of the sediment yield parameters (Tables 7 and 8) shows that CASC2D-SED was able to compute sediment yield to within 65% of the observed sediment yield at the outlet. However, some of the gauges within the watershed showed a rather high volume of computed upland erosion when compared to the total
observed sediment yield (400%). The crop management factors used for this simulation reflect values associated with high land disturbance. Since this event occurred in December, when farming practices were at a minimum, a reduction in the crop management factor for the row crop and pasture seems to be in order.

A comparison of the hydrograph parameters, for storm event 3 (Tables 4 to 6) shows that the model was able to simulate the overall shape, rate of rise, and the total volume of runoff. However, for this simulation, CASC2D-SED was off at selected locations on the time to peak and the peak flow. At the outlet, the measured peak flow was 3662.3 and CASC2D-SED computed the peak flow to be 3743.5, so CASC2D-SED estimated the peak flow at the watershed outlet to within 2.2%. At gauge 3, the measured peak flow was estimated to be 3193.7 and CASC2D-SED computed a peak flow of 1936.5. Since all of the other gauges seemed to compare relatively well (1% to 30%) with the observed peak flow measurements, the difference at gauge 3 seems to be out of place and may suggest some error in the instrumentation at this gauge site. The time to peak was off by a rather large amount at the outlet, with the difference between measured and computed being 46 min. In the upper portion of the watershed, the time to peak was too fast by approximately 15 min with the difference increasing as the flow moved down the watershed.

A comparison of the sediment yield parameters (Tables 7 and 8) shows CASC2D-SED computing upland erosion within acceptable ranges at most of the gauges (−50%
to 200%): Gauges 4, 9 and 14 show upland erosion amounts to be a little high (125% to 265%), but again, since the model is using average annual crop management factors and not taking into account seasonal variations, this can be expected. At the outlet, the observed sediment yield was 10487.6 tons and 1.98 tons/acre, while CASC2D-SED computed the upland erosion component to be 3647.0 tons and 0.69 tons/acre. This results in a percentage of total sediment yield due to upland erosion of 34.8%.

CONCLUSIONS

CASC2D-SED is well suited for the simulation of sediment yield from upland areas. The model provides two-dimensional colour maps of sediment-flux, suspended sediment volume, and net aggradation/degradation during the course of single rainstorm events. The model has been tested on Goodwin Creek.

From the results of the three storm events discussed in this paper, CASC2D-SED was able to accurately simulate the rainfall–runoff processes on the watershed scale. 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. The CASC2D-SED upland erosion scheme computed sediment yield within a reasonable limit (~50% to 200%).

REFERENCES


