CHAPTER 3

THE REVISED CASC2D-SED MODEL

"The future of watershed models will be shaped by increasing societal demand for integrated environmental management; growing need for globalization by incorporation of biological, chemical, and physical aspects of the hydrologic cycle; rapid advances in remote sensing and satellite technology, geographical information systems (GIS) database management systems (DBMS), and expert systems; enhanced role of models in planning and decision making; mounting pressure on transformation of models to user-friendly levels; and clearer statement of reliability and risk associated with model results."

Vijay P. Singh, 1995

The CASC2D-SED program governing equations including the newly implemented interception process are reviewed in this chapter. The revised upland erosion and sediment transport and the implementation of the channel sediment routing are described as well.

In the second part, the implementation of the CASC2D-SED output time-series grids visualization in Arc/Info® is explained.

CASC2D-SED source code, input/output files and variables definitions are listed in Appendix I. AML programs for the output grids time-series animation are also found in Appendix I.

3.1. MODEL DEVELOPMENT

The CASCade 2 Dimensional SEDimentation (CASC2D-SED) model originally began with a two-dimensional overland flow routing algorithm developed and written in APL by Prof. P.Y. Julien at Colorado State University. The overland flow routing module was converted from APL to FORTRAN by Dr. Bahram Saghafian, then at Colorado State University, with the addition of Green & Ampt infiltration, detention storage and diffusive-wave channel routing (Julien and Saghafian, 1991; Saghafian, 1992; Julien *et al.*, 1995).

CASC2D was incorporated as part of the GRASS GIS for hydrologic simulations as r.hydro.CASC2D (Sagahfian, 1993; Sagahfian and Ogden, 1996). Later on, Ogden (1994) added implicit channel routing option to CASC2D. Since 1995, CASC2D has been reformulated with the addition of continuous simulation capabilities and other hydrological components such as interception, initial depths, evapotranspiration and redistribution (Ogden, 1997a). This last version is incorporated in the Watershed Modeling System Interface developed by Brigham Young University (2001) and is known as CASC2D for WMS. CASC2D/WMS development and integration is funded by the U.S. Army Corps of Engineers, Waterways Experiment Station. The integrated version of CASC2D-SED in WMS interface may be used only by the Corps of Engineers and in educational institutions.

The upland erosion module was added by Dr. Billy Johnson (1997) based in previous work done by Kilinc (1972) and Kilinc and Richardson (1973) at Colorado State University and was called CASC2D-SED. Figure shows the CASC2D-SED model flowchart. The new or revised part of the model is shown in bold letters.

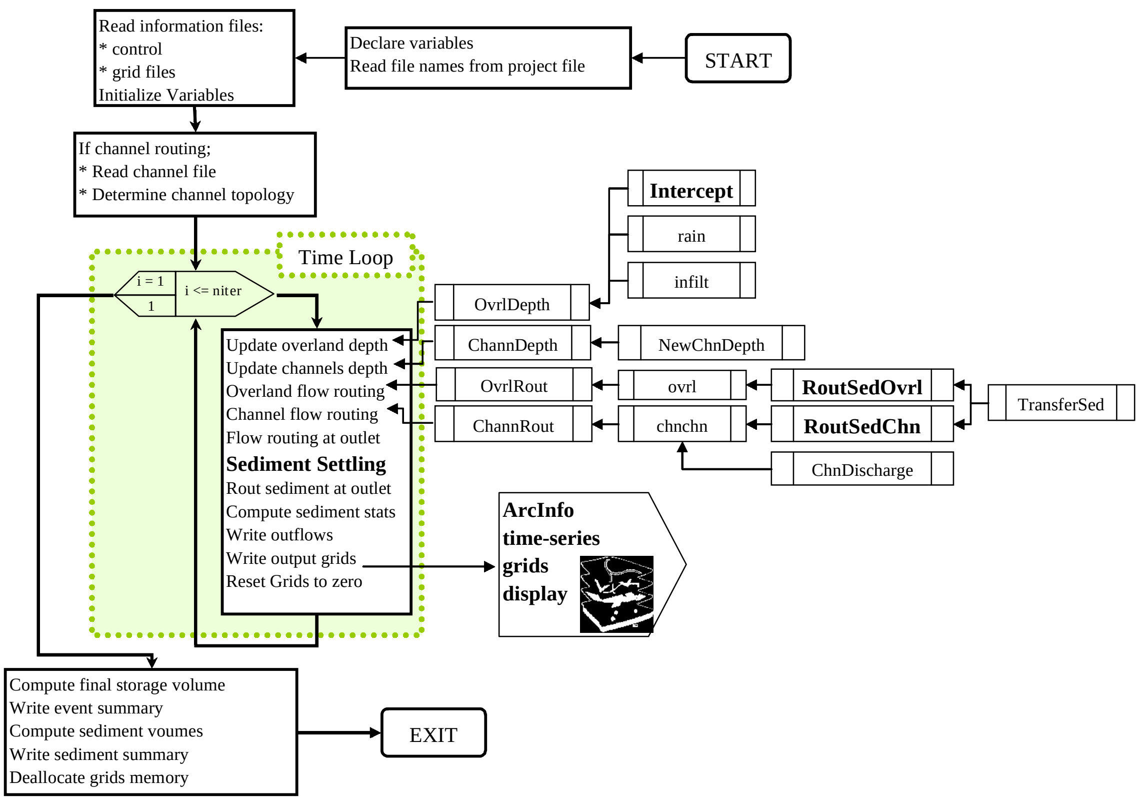


Figure 3-1. CASC2D-SED flowchart and revised/new code (in bold letters)

3.2. CASC2D-SED DESCRIPTION

CASC2D has been developed to determine the runoff hydrograph generated from any temporally-spatially varied rainfall event. When using the erosion/sedimentation module of CASC2D, sediment rates can be predicted at any location as well.

For a given rainfall event, once the initial losses have been subtracted from rainfall, water begins to infiltrate. This step requires the adoption of an infiltration scheme that can predict the portion of the rainfall that drains into the ground. The Green & Ampt (1911) infiltration equation accommodates spatial and temporal variabilities due to changes in the rainfall and/or soils properties, and takes into account the accumulated infiltration.

Using a Hortonian overland flow process, when the precipitation rate exceeds the infiltration rate, the excess rainfall will accumulate as surface water and begin to flow. In CASC2D, overland flow is routed into the channels using a diffusive wave approximation in two dimensions. In channels, the water is routed using a 1-D diffusive wave equation.

The erosion/sedimentation rates are calculated as a function of the hydraulic properties of the flow, the physical properties of the soil and the surface characteristics. The modified Kilinc-Richardson equation (Julien, 1995) is used in CASC2D-SED to determine the upland sediment transport by grain size (silt, clay, and sand) from one cell into the next one in two orthogonal directions.

CASC2D solves the equations of conservation of mass, energy and linear momentum to estimate watershed runoff for a given rainfall input. The overland flow routing formulation is based on an explicit 2-D finite difference (FD) technique. The channel formulation is based on an explicit 1-D FD technique.

In the next section, the governing equations in the overland flow and channel routing schemes are described. The equations used in estimating precipitation, interception and infiltration rates are also included. Finally, the processes of sediment transport on overland and channel cells are described.

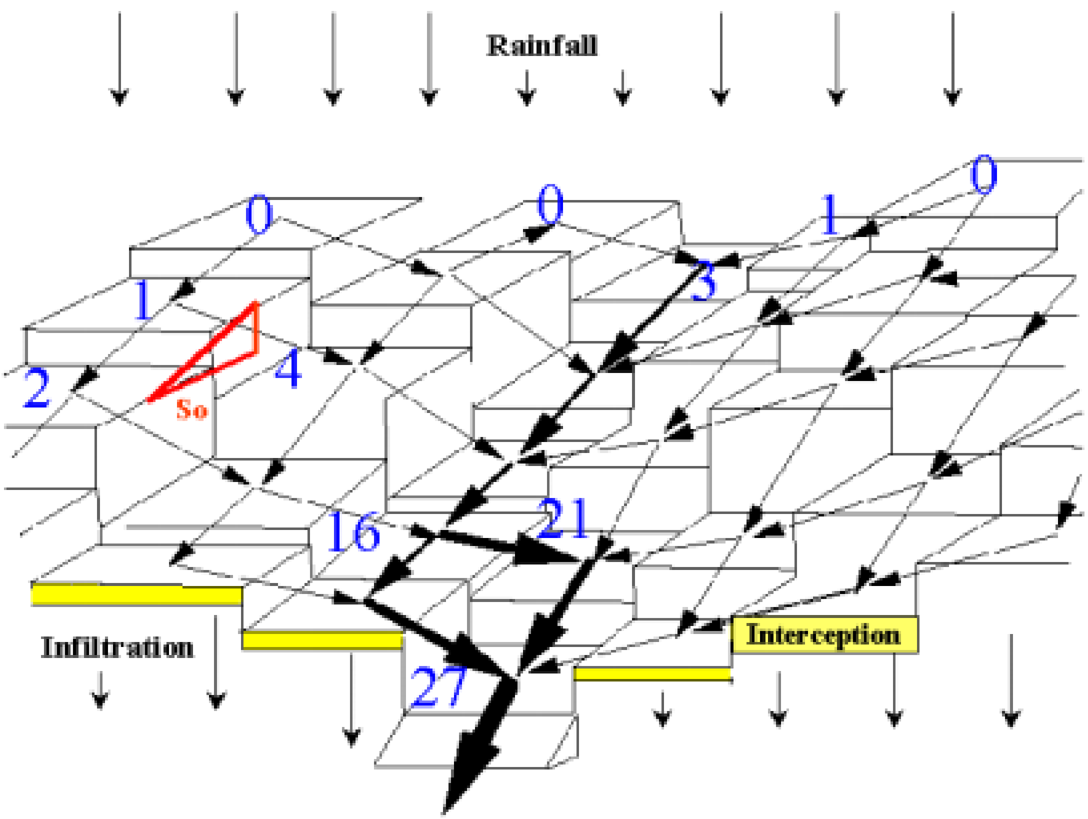


Figure 3-2 Topographical representation of overland flow and channel routing schemes

3.3. FLOW ROUTING ALGORITHM

3.3.1. Precipitation

When more than one rain gage is used in the estimation of the precipitation, an interpolation scheme based on the inverse distance squared approximates the distribution of rainfall intensity over the watershed:

$$i^t(j,k) = \frac{\sum_{m=1}^{NRG} \frac{i_m^t(jrg,krg)}{d_m^2}}{\sum_{m=1}^{NRG} \frac{1}{d_m^2}} \qquad [3\text{-}1]$$

where,

$i^t(j,k)$ = rainfall intensity in element (j,k) at time t

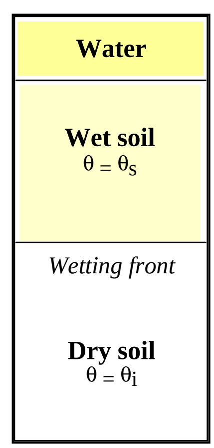
$i_m^t(jrg,krg)$ = rainfall intensity recorded by the m-th rainfall gage located at (jrg,krg)

d_m = distance from element (j,k) to m-th rain gage located at (jrg,krg)

NRG = total number of rain gages

3.3.2. Interception

As rain falls on a vegetated surface, part of it is held on the foliage by surface tension forces. Rather than reaching eventually the ground, this portion of the rainfall evaporates directly and does not take part in ultimate runoff and thus, it is usually termed interception loss (Eagleson, 1970). Chow (1988) defines as retention the part of the surface storage held for a long period of time and depleted by evaporation.



Because intercepted water does not reach the soil surface, it has no part in infiltration. Accordingly, the interception depth is subtracted from the rainfall before infiltration is calculated. In CASC2D-SED, the rainfall rate is reduced until the interception depth (I) has been satisfied. For a given grid cell inside the basin, if the total rain falling during the first time increment (dt) is greater than I, the rainfall rate is reduced by I/dt. If the rainfall depth is less than I, the rainfall rate is set to zero and the remainder of the interception is removed from the rainfall in the following time increments.

3.3.3. Infiltration

The Green and Ampt equation (1911) provides the primary relationship for infiltration within the CASC2D computer model. The Green and Ampt infiltration scheme gained considerable attention partially due to the ever growing trend of physically-based hydrological modeling (Philip, 1983). To accurately account for the physical process involved with surface flow, CASC2D uses the Green and Ampt approximation for soil infiltration. Specifically, this relationship is utilized within the model's infiltration scheme to determine the depth and rate of soil infiltration as a component of the resulting overland flow.

The Green-Ampt model assumes piston flow with a sharp wetting front between the infiltration zone and soil at the initial water content. The wet zone increases in length as infiltration progresses (Bras, 1990).

Neglecting the level of ponding on the surface, the general equation showing the Green-Ampt relationship can be expressed as (Bras, 1990):

$$f = Ks\left(1 + \frac{H_f M_d}{F}\right) \qquad [3\text{-}2]$$

where:
f = infiltration rate
K_s = saturated hydraulic conductivity

H_f = capillary pressure head at the wetting front
M_d = soil moisture deficit = $(\theta_e - \theta_i)$
θ_e = effective porosity = $(\varphi - \theta_r)$
φ = total soil porosity
θ_r = residual saturation
θ_i = soil initial moisture content
F = total infiltrated depth

To apply this calculation to the entire watershed area, four separate physical characteristics must be known and provided as input to the model. These characteristics are hydraulic conductivity, capillary pressure, effective soil porosity, and initial soil moisture content. Their numerical values can be obtained from the experimental data by Rawls *et al.* (1983) depending on the soil texture.

3.3.4. Overland Flow

The governing equations for overland flow with the CASC2D Model are based primarily on the de-Saint Venant Equations of continuity and momentum. Using these formulations, CASC2D was designed around an explicit finite difference, diffusive-wave method to route overland flow. The general form for these equations, as shown in Julien and Saghafian (1991), are commonly expressed in partial differential form as:

Continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = e \qquad [3\text{-}3]$$

Momentum:

x-direction
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = g(S_{ox} - S_{fx} - \frac{\partial h}{\partial x}) \qquad [3\text{-}4]$$

y-direction $$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=g(S_{oy}-S_{fy}-\frac{\partial h}{\partial y})$$ [3-5]

where:

h	=	surface flow depth
q_x	=	unit flow rate in the x-direction,
q_y	=	unit flow rate in the y-direction
e	=	excess rainfall (i-f)
i	=	rainfall intensity
f	=	infiltration rate
x,y	=	Cartesian spatial coordinates
t	=	time
$S_{o(x,y)}$	=	bed slopes in the x- and y-direction, respectively
$S_{f(x,y)}$	=	friction slopes in the x- and y-direction, respectively
u,v	=	average velocities in the respective x- and y- directions
g	=	gravitational acceleration

Equations 3.4 and 3.5 show the relationship between the net forces per unit mass in each direction and the acceleration of flow in relation to that given direction. Thus, the forces along a given axis are shown on the right side of the equation, while the local and convective acceleration is given by the left-hand side of the equation. The simplified diffusive approximation for Equations 3.4 and 3.5 assumes that the net forces acting along the given axis of interest are approximately zero. Thus, the resulting diffusive wave approximation can be descried by the following equations.

$$S_{fx}=S_{ox}-\frac{\partial h}{\partial x}$$ [3-6]

$$S_{fy}=S_{oy}-\frac{\partial h}{\partial y}$$ [3-7]

The key advantage that is provided in using the diffusive form of the momentum equations is the ability to account for backwater effects observed during overland and channel flow events.

Using the three equations given for continuity and momentum, a resistance law can be established. This equation relates flow rate to depth and other given flow parameters such as surface roughness. The defined resistance law can be derived for either the x or y-directions as:

$$q_{x,y} = \alpha_{x,y} h^{\beta} \qquad [3\text{-}8]$$

In this form $\alpha_{x,y}$ and β are flow regime parameters that vary depending on whether turbulent or laminar conditions exist. CASC2D assumes turbulent conditions for the entire watershed and the Manning approximation for $\alpha_{x,y}$ and β are determined to be:

$$\alpha_{x,y} = \frac{S_{f(x,y)}^{1/2}}{n} \qquad [3\text{-}9]$$

$$\beta = \frac{5}{3} \qquad [3\text{-}10]$$

Where n is the Manning roughness coefficient, or surface roughness. This coefficient can be estimated from the land use map using the values provided by Woolhiser (1975).

3.3.5. Channel Flow

The channel routing scheme employed by CASC2D is capable of processing completely unsteady hydraulic scenarios. This is achieved by the use of a one-dimensional diffusive channel flow equation (Julien and Saghafian, 1991). The governing equations for the channel flow routing process are similar to those for overland flow, with one significant exception to note. The equations used in channel flow routing are defined by a finite width established for a given channel section. The one-dimensional continuity relationship can be expressed by the following equation (Julien and Saghafian, 1991):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l \qquad [3\text{-}11]$$

where:

A	=	channel flow cross-sectional Area
Q	=	total channel discharge
q_l	=	lateral inflow rate per unit length (into or out of the channel)

Once again, by assuming the flow within the channel is completely turbulent, the model utilizes Manning's equation to ascertain a value for channel flow equation (Julien and Saghafian, 1991).

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S_f^{\frac{1}{2}} \qquad [3\text{-}12]$$

where:

R	=	hydraulic radius
S_f	=	friction slope
n	=	Manning roughness coefficient

3.4. SEDIMENT ROUTING ALGORITHM

3.4.1. New Sediment Transport Approximation

Once a soil particle erodes, it becomes part of the flow and is transported downstream. A particle moving past a control must have eroded somewhere in the watershed upstream of the cross section, and it must be transported by the flow from the point of detachment to the point of interest (Einstein,1950). Each of these two requirements may control the sediment rate at the cross section: the availability of sediment in the watershed and the transport capacity of the stream. Typically, the finer material, which is easily carried in large amounts by the flow, has limited availability in the watershed. The coarse material is much more difficult to move by flows, so its rate of movement is limited by the transport capacity of the flow (Haan, 1994). Julien (1995) uses Figure 3-2 to explain the concept of supply and transport limited capacity.

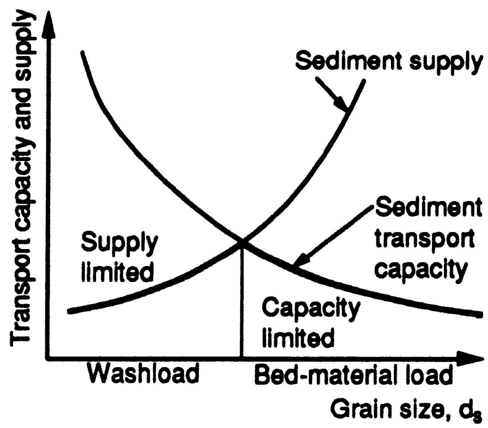


Figure 3-3. Sediment transport capacity and supply curves (Julien, 1995)

It is often assumed that the washload travel through a system by streamflow with very little deposition and is carried primarily in suspension. Coarser fractions tend to move as bed-material. In addition, particles moving in suspension at one place may be moving as bed-material further downstream. The total sediment discharge or total sediment load, consist of both bed-material load and washload. Generally, total sediment load can only be estimated if the washload is estimated by measurements, experiment, or upland sediment yield equation because most sediment transport methods can only determine bed-material load (Haan, 1994).

Streamwise velocity of sediment particles always lag behind the velocity of the surrounding fluid. This lag is small for the case of silt particles in suspension and large for the case of sands and gravels (Francis, 1973). Thus, it is important to predict the movement of the individual sizes found in the flow (Borah, 1982).

The overland sediment transport routine in CASC2D-SED has been extended to simulate the described transport processes. In the overland, CASC2D-SED uses the modified Kilinc and Richardson (1973) transport capacity, which depends on flow discharge, terrain slope and soil and land use characteristics. Small particles such as clay and silt move mostly in suspension while the sand fraction moves as bed-material. This is accomplished by using the particle settling concept and the transport of suspended material by advective processes. With a large settling velocity, the eroded sand fraction brought into suspension rapidly settles while the small fractions such as clay tend to remain in suspension due to its low settling velocity. Once it is in suspension, the suspended size fraction moves by advection. The advective fluxes describe the transport of sediments imparted by velocity currents (Julien, 1995). This implies that sediment will move with the fluid even for capacity limited conditions. The excess transport capacity is defined as the flow capacity to move the bed-material and produce erosion of the parent. First, the excess transport capacity is used to move the sediment by size fraction according to its percentage in the bed-material. Then, if there is any remaining transport capacity once the suspended and bed-material have been transported, the soil is eroded proportionally to the percentage of the corresponding size fraction in the parent material. See Figure 3-4 for overland erosion and sediment transport processes flowchart.

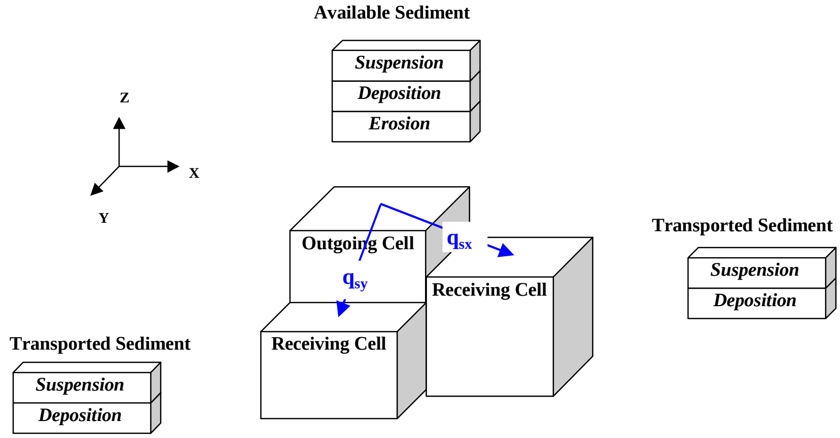


Figure 3-4 Schematic of upland sediment transport (Johnson, 1997)

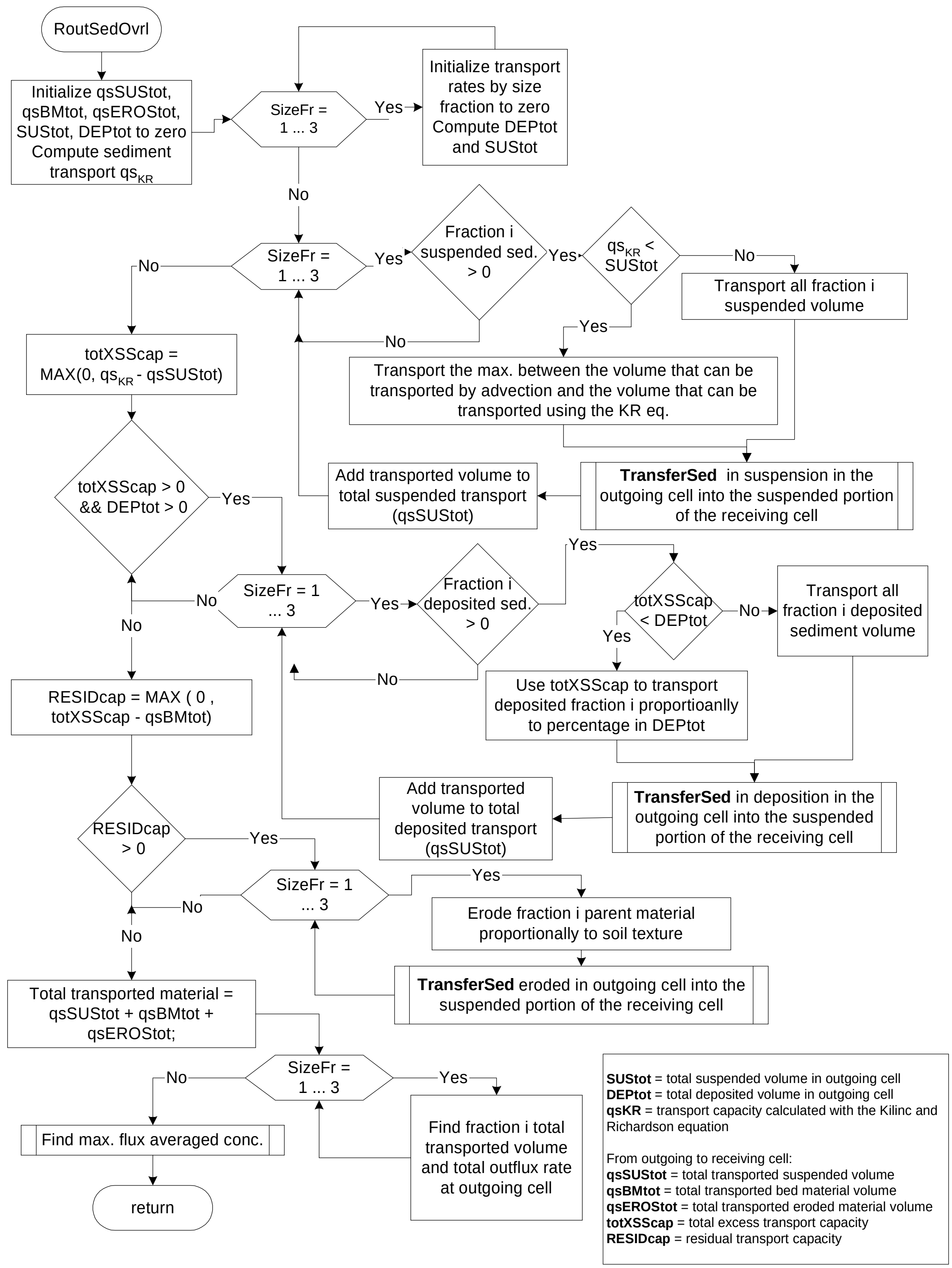


Figure 3-5. Overland erosion and sediment routing flowchart

Sediment by size fraction is routed in the channels using the Engelund and Hansen (1967) equation in 1-D. This formulation depends on hydraulic parameters (hydraulic radius, flow velocity and friction slope) and particle characteristics (specific gravity and particle diameter). For each of those fractions, a transport capacity is calculated using the Engelund and Hansen equation. For a particular size fraction, once the amount of sediment carried in suspension by advective processes has been subtracted from the transport capacity, the bed-material is transported using the excess transport capacity. The amount of transported bed-material will be the minimum between the amount that can be carried by advective processes and the excess transport capacity. Channels are not allowed to erode in CASC2D-SED and thus, the remaining transport capacity is not used. The differential treatment between the transport of the fine material as washload and the sand as bedload is accomplished through different transport capacities (as calculated with the Engelund and Hansen equation) and the differences in the settling velocities for each size fraction.

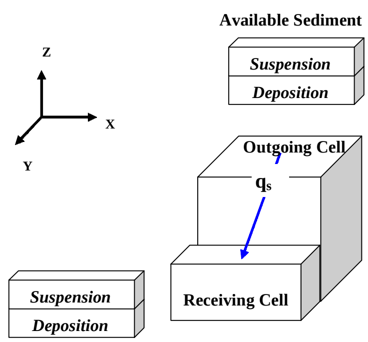


Figure 3-6. Schematic of channel sediment transport

The transported material (from suspension, bed-material or parent material) is transferred from the outgoing cell into the suspended portion of the receiving cell. Once the sediment has been routed for all the overland and channel cells in the watershed in the x- and y-direction, the sediment in suspension is allowed to settle. For a given sediment size fraction at a given cell, the volume of suspended sediment that will settle depends on the total volume of that fraction in suspension, on the particle settling velocity and the water depth at the given cell. See Figure 3-6 for channel sediment routing processes flowchart.

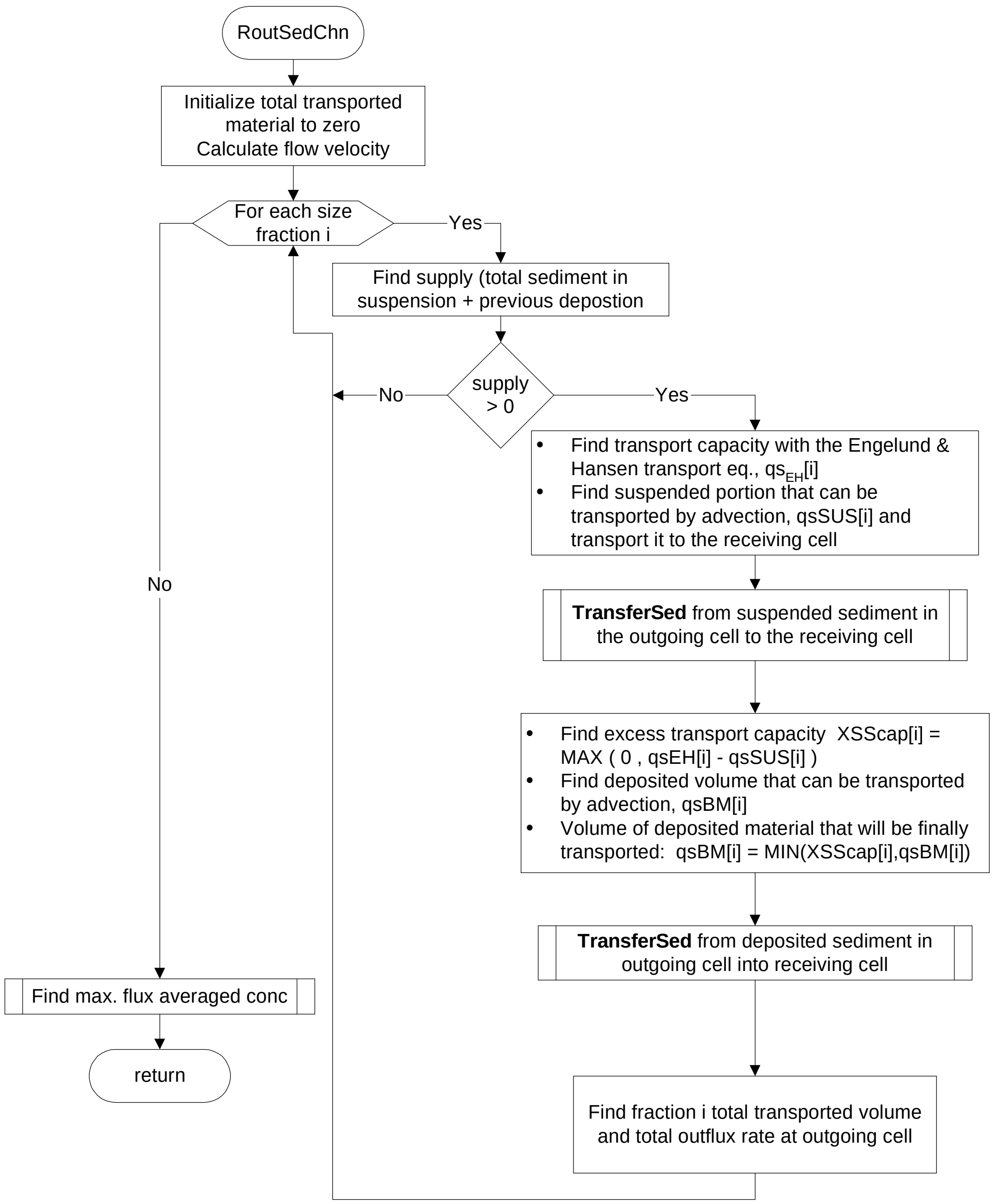


Figure 3-7. Channel sediment routing flowchart

3.4.2. Revised Upland Erosion and Sediment Transport

Julien and Simons (1984) derived a general relationship supported by dimensional analysis that can be written as a power function of slope and discharge. The unit upland sediment discharge from sheet and rill erosion can be written in the form (Julien and Simons, 1984):

$$q_s = \alpha \, S_o^{\beta} q^{\gamma} \qquad [3\text{-}13]$$

where:

So	=	surface slope (m/m)
q	=	unit discharge (m^2/s)
q_s	=	sediment unit discharge
α, β, γ	=	coefficients

Several empirical equations were transformed to evaluate the β and γ exponents. Among these equations are those of Musgrave (1957), Li, Shen and Simons (1973), and Kilinc (1972). The values of the exponents β and γ range typically between $1.2 < \beta < 1.9$ and $1.4 < \gamma < 2.4$ (Julien and Simons, 1984).

In 1972, Kilinc studied experimentally and analytically the mechanics of soil erosion from overland flow generated by simulated rainfall. The main objectives of his research were to study the most important factors affecting soil erosion, and to develop a soil loss prediction equation. Experiments were conducted at the rainfall-runoff facilities at the Engineering Research Center of the Colorado State University. Data was collected for sediment concentration, surface velocity of overland flow, water discharge, water temperature, infiltration rate, bulk density of surface soil, slope, intensity of rainfall, and rill geometry. Some of the conclusions from derived from the study of Kilinc were: a) the Reynolds number and slope were the most important parameters in sediment transport prediction equations, b) the Reynolds number, rainfall excess, and water discharge each had the same significance and influence on sediment transport from overland flow, c) sediment discharge increases with the square of water discharge, q, and 5/3 power of the slope. This model was comparable to that used by Meyer and Wischmeier (1969).

The equation of Kilinc and Richardson (1973) is recommended by Julien (1995) for the estimation of sheet and rill erosion in bare soils:

$$q_s = e^{11.727} S_o^{1.664} q^{2.035} \qquad [3\text{-}14]$$

where:

qs	=	unit sediment discharge [lb ft^{-1} s^{-1}]
S_o	=	terrain slope [m/m]
q	=	unit flow discharge [ft^2 s^{-1}]

In the more general case of erosion from sheet flow, modifications to the last equation reflect the influence of soil type, vegetation, and practice factor using the USLE factors K, C, and P as (Julien, 1995):

$$q_s = 23210 S_o^{1.66} q^{2.035} \frac{K}{0.15} C P \qquad [3\text{-}15]$$

where:

qs	=	unit sediment discharge [tons m^{-1} s^{-1}]
q	=	unit flow discharge [m^2 s^{-1}]
K	=	dimensionless erodibility factor in the USLE equation
C	=	cropping management factor in the USLE equation
P	=	conservation practice factor in the USLE equation

The total upland erosion is calculated as:

$$Au = \int_{time} \int_{width} q_s .dw.dt \qquad [3\text{-}16]$$

For a grid of cell size, w, and for a time interval, dt, the total volume (in m^3) of sediment coming from a cell is calculated as:

$$Q_{s\,KR} = 58390 * S_o^{1.664} * q^{2.035} * K * C * P * w * dt \qquad [3\text{-}17]$$

The rate of mass transport carried by advection, qs_{ADVi} [m^3 s^{-1}] is obtained from the product of sediment concentration and the velocity component (Julien, 1995):

$$\frac{qs_{ADV\,i}}{A} = V * Ci \qquad [3\text{-}18]$$

where:

qs_{ADVi} = size fraction i sediment transport [m^3 s^{-1}]
A = flow area [m^2]
V = average flow velocity [m s^{-1}]
Ci = suspended size fraction i concentration [m^3 m^{-3}]

Simplifying and integrating for a time step dt, the volume (in m^3) of suspended sediment size fraction, i, that can be transported by advection (Qs_{SUSi}) is:

$$Qs_{SUS\,i} = SusVol_i * \frac{V * dt}{w} \qquad [3\text{-}19]$$

where:

$SusVol_i$ = Size fraction i suspended volume [m^3]
w = grid cell size [m]

the volume of suspended sediment that will be finally transported is found as:

$$\begin{aligned} Qs_{SUS\,i} &= MAX\left(Qs_{SUS\,i} \ ; \ Qs_{KR} * \frac{SusVol_i}{\sum_{i=1}^{3} SusVol_i} \right) \qquad if \quad Qs_{KR} < \sum_{i=1}^{3} SusVol_i \\ Qs_{SUS\,i} &= SusVol_i \qquad otherwise \end{aligned} \qquad [3\text{-}20]$$

The total excess capacity (totXSScap) of the flow to carry sediments from the bed-material is calculated as:

$$totXSScap = MAX(0\ ;\ qs_{KR} - \sum_{i=1}^{3} Qs_{SUS\,i}) \qquad [3\text{-}21]$$

And the volume (in m^3) of size fraction i transported from the bed-material, Qs_{BMi}, is found as:

$$Qs_{BM\,i} = totXSScap * \frac{BMvol_i}{\sum_{i=1}^{3} BMvol_i} \qquad if \quad totXSScap < \sum_{i=1}^{3} BMvol_i$$

$$Qs_{BM\,i} = BMvol_i \qquad otherwise \qquad [3\text{-}22]$$

where $BMvol_i$ is the volume of size fraction i found in the bed-material

Once the sediment in suspension and the bed-material are transported and provided that there is still remaining capacity left, the soil is eroded proportionally to the percentage of fraction i in the parent material, P_i:

$$Qs_{EROS\,i} = (totXSScap - \sum_{i=1}^{3} Qs_{BM\,i}) * P_i \qquad [3\text{-}23]$$

where Qs_{EROSi} is the volume (in m^3) of size fraction i eroded from the parent material.

3.4.3. Implementation of Channel Sediment Transport

The eroded material in the upland portion of the watershed is transported to the outlet through the channels. Erosion is not allowed to occur in the channels. Thus, transport might be supply limited. Deposition of material is allowed. The Engelund and

Hansen (1967) equation is used to calculate the sediment transport capacity in the channels.

Engelund and Hansen applied Bagnold's stream power concept and the similarity principle to obtain the sediment concentration by weight as follows (Julien, 1995):

$$Cwi = 0.05 * \left(\frac{G}{G-1} \right) * \frac{V * Sf}{\sqrt{(G-1) * g * dsi}} * \sqrt{\frac{Rh * Sf}{(G-1) * dsi}}$$

where:

G	=	specific gravity of sediment [--]
V	=	channel depth-averaged velocity [m/s]
Sf	=	channel friction slope [m/m]
g	=	gravitational acceleration [m2/s]
dsi	=	size fraction i diameter [m]
Rh	=	channel hydraulic radius [m]

and the volume of size fraction, i, that can be transported during a time interval, dt, is estimated as:

$$Qs_{EH\,i} = \frac{Q * Cw_{i} * dt}{2.65} \quad [3\text{-}24]$$

where Q [m^3 s^{-1}] is the flow discharge in the channel and Cwi is the sediment concentration by weight of size fraction i.

The volume (in m^3) of suspended sediment size fraction, i, that is transported in the channels by advection ($Qs_{SUS}i$) is:

$$Qs_{SUS\,i} = SusVol_i * \frac{V * dt}{w} \quad [3\text{-}25]$$

The excess capacity to carry size fraction i channel bed-material, $XSScap_i$, is found as:

$$XSScap_i = MAX(0\ ;\ Qs_{EH\,i} - Qs_{SUS\,i}) \quad [3\text{-}26]$$

while the volume of fraction, i, bed-material (Qs_{BMi}) that can be transported by advection in the channel is proportional to:

$$BMvol_i * \frac{V * dt}{w} \qquad [3\text{-}27]$$

where $BMvol_i$ is the volume of size fraction i found in the bed-material. The volume of size i bed-material that will be finally transported from the bed-material, Qs_{BMi}, is found to be the minimum between the excess capacity and the volume of the bed-material that can be carried by advection for that size fraction:

$$Qs_{BM\,i} = MIN(XSScap_i \;;\, BMvol_i \; * \frac{V * dt}{w}) \qquad [3\text{-}28]$$

In the case in which there is still remaining transport capacity, this will not be used, as channels are not currently allowed to erode in CASC2D-SED.

3.4.4. Suspended Sediment Settling

The former sediment deposition of sediments in CASC2D-SED using the trap efficiency concept (Johnson, 1997) has been substituted by the sediment settling concept. Two are the reasons for this change. First, for the very low water depths simulated in overland cells, the trap efficiency calculated for the sand and silt fractions was for most of the simulations equal to one. This is, all the sand and silt fractions moved as bed load, independently of the silt fraction having a much smaller settling velocity. The second reason is that for no flow conditions, for example in concave areas or sinks, the sediment remained in suspension, even after all the water had infiltrated at the end of the simulation. Using the simple concept of sediment settling once all the sediment has been routed from one cell to the next at each time step, these two inconsistencies were finally solved. Sand, silt and clay fractions may deposit proportionally to their settling velocities, thus allowing for a differential treatment of sediment routing by size fraction. The suspended sediment may deposit for no flow conditions, and once all the surface water has been infiltrated, there is no sediment in suspension left.

A particle falling in turbulent free water moves in response to the difference in the submerged weight of the particle and the drag of the fluid on the particle. At steady state, the forces in equilibrium are described by:

$$CD\left[\frac{\pi d^2}{4}\right]\left[\frac{\rho\,\omega_s^2}{2}\right]=\frac{\pi d^3}{6}(\rho_S-\rho)g \qquad [\ 3\text{-}29]$$

where:

CD	=	drag coefficient, normally a function of the Reynolds number, Re
d	=	particle diameter
ρ_s	=	particle density
ρ	=	fluid density
ω_s	=	particle settling velocity
g	=	acceleration of gravity

Stokes showed that the drag for spheres depends on the Reynold's number:

$$CD = {}^{24}\!/_{\mathrm{Re}} \qquad [3\text{-}30]$$

where Re depends on the kinematic viscosity, ν:

$$\mathrm{Re} = {}^{\omega_s\ d}\!/_{\upsilon} \qquad [3\text{-}31]$$

For the Stokes' range (i.e. Re < 0.5). Equation 3-30 can be simplified to yield (Haan, 1994; Julien, 1995):

$$\omega_s = \frac{1}{18}\left[\frac{d^2 g}{\upsilon}(G-1)\right] \qquad [3\text{-}32]$$

where G is the specific gravity of the particles. The settling velocity of large particles (> 0.2 mm and Re > 0.5), can be estimated with the following relationship (Julien, 1995):

$$\omega_s = \frac{8\,\upsilon}{d}\left\{\left[1 + 0.0139\, d^3\, \frac{(G-1)\,g}{\upsilon^2}\right]^{0.5} - 1\right\} \qquad [3\text{-}33]$$

Assuming, medium sediment particle diameter for the sand, silt and clay fractions, the following fall velocities are estimated:

Table 3-1. Particle mean diameter and fall velocity

Size fraction	d [mm]	ω_s [m/s]
Sand	0.35	0.036
Silt	0.016	2.20E-04
Clay	0.001	8.60E-07

After routing the sediment from the outgoing into the receiving cell, the sediment in suspension is allowed to settle. CASC2D-SED assumes a discrete particle settling type in which particles tend to fall independently of each other as discrete particles. The percentage of suspended sediment that will deposit for an increment of time, dt, depends on the particle settling velocity, ω_i, and the cell water depth, h:

$$\begin{aligned} PercSett_i &= \omega_i \frac{dt}{h} && \text{if} \quad h > \omega_i * dt \\ PercSett_i &= 1 && \text{otherwise} \end{aligned} \qquad [3\text{-}34]$$

The volume of suspended sediment that settles in a given time increment is subtracted from the suspended sediment portion and added to the deposited one.

3.5. CASC2D-SED GRIDS TIME-SERIES VISUALIZATION

CASC2D-SED generates a series of Arc/Info® ASCII grids at specified time intervals during simulation. These grids show the interpolated excess rainfall intensity, water depth in overland and channel cells, and infiltrated rainfall volume. When the erosion option is selected, suspended sediment volume and concentration, net erosion depth, sediment flux by size fraction, and maximum flux-averaged sediment flux by size fraction can be displayed.

Currently, CASC2D-SED is loosely coupled with Arc/Info to display the outputs as a sequence of grids. Arc/Info's Arc Macro Language (AML) is used to convert the CASC2D-SED output (in ASCII format) to Arc/Info grid format and display them sequentially in a layout in ArcPlot (see Appendix I).It is possible to create layouts with 1, 2, 3, 4 and 6 thematic grids, their corresponding titles and legends and simulation time. The grids are reclassified according to the remap tables defined by the user. For the sequential display, the user may select the start and ending grid to display, as well as the time to delay the display between two sequential layouts.

MPEG is a compression standard for audio, video, and data designed to produce reasonable quality images and sound at low bit rates. The Berkeley MPEG-1 video encoder[2] is a free software that can be used in the generation of a MPEG video from image files. From the ArcPlot display, an image file is created for each layout. This image is later copied several times and finally fed into the Berkeley encoder to create a MPEG file.

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[2] http://bmrc.berkeley.edu/frame/research/mpeg/

3.6. SUMMARY

In this chapter:

(1) The interception process has been implemented in CASC2D-SED adding for physical realism of the model.

(2) The upland erosion routing scheme has been revised to include sediment transport by advective processes. Suspended sediment may move as washload even in capacity limited conditions. In supply limited conditions, the suspended sediment is transported by size fraction proportionally to the amount of this size fraction in suspension. If the transport capacity is greater than the volume of suspended sediment, the previously deposited sediment is transported by size fraction, again, proportionally to the amount of the given size fraction in the deposited sediment. Subsequent excess transport capacity corresponds to erosion of the parent soil with size fractions in proportion to the soil texture.

(3) The sediment routing by size fraction in channels has been added. The eroded material in the upland portion of the watershed is transported to the outlet through the channels. Currently, channels are not allowed to erode, thus, transport might be supply limited. Deposition of material is allowed. Suspended sediment moves downstream as washload by advection implying that sediment will move with the fluid even when the transport rate is lower or higher than the transport capacity. This means a supply limited transport in some cases and a capacity limited transport conditions in others. Like for the routing of the sediment in the overland portion, the transport capacity is fulfilled, first, with the suspended sediment volume and, if needed, with the previously deposited sediment. The excess transport capacity is defined as the flow capacity to move the bed-material once the sediment transported by advection is subtracted. For each size fraction, the amount of bed-material that will be transported is limited by the amount that can be transport by the flow (advection) or by the excess transport capacity. In the case in which there is still remaining transport capacity, this will not be used, as the channels are not currently allowed to erode in CASC2D-SED. The fine sediment fraction has larger transport capacity than the coarser fraction and a smaller settling velocity making the finer fractions to move downstream as washload more rapidly than the sand fraction.

(4) The former trap efficiency has been traded with the sediment settling concept. This allows deposition of the sediment for no flow conditions. It also allows for a differential treatment in the silt and sand fractions routing in the upland portion of the basin. The low settling velocities corresponding to the finer sizes (silt and clay) make them to stay in suspension and so they move as washload with the flow.

(5) The program time-series output grids may be displayed automatically in the Arc Plot module of Arc/Info® with the aid of the AML programming language. An MPEG file may be generated with the use of the freeware Berkeley encoder