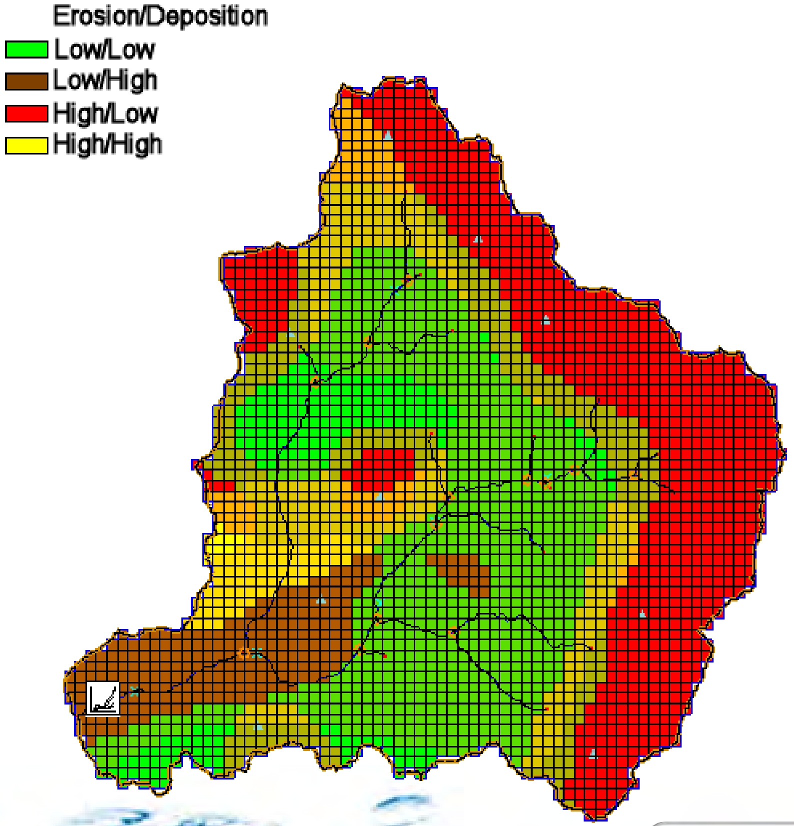
Sedimentation Transport Modeling in GSSHA

Sediment Transport Overview

- Event based erosion and deposition model (not USLE-based)
  - Overland
  - Streams
- User-defined sediment properties

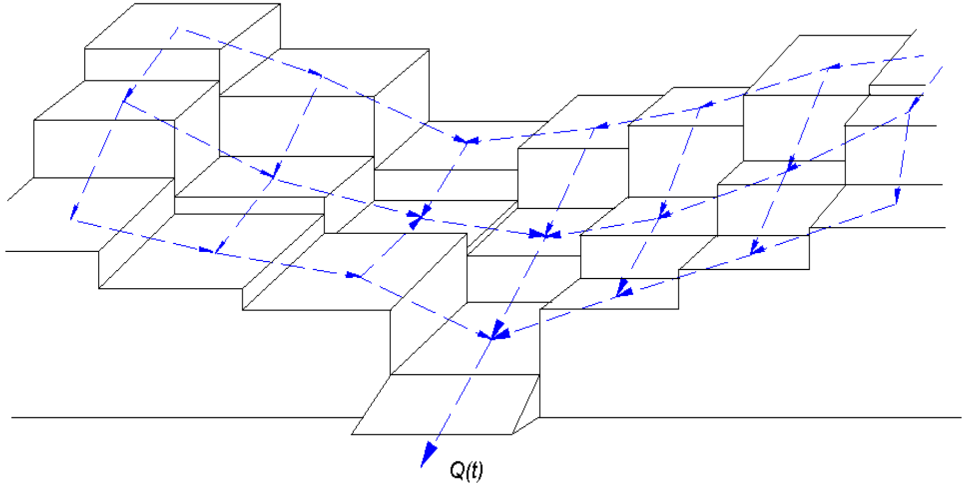


GSSHA Sediment Transport Processes

- Simulation of sediment erosion from the overland plane
- Transport across overland plane including deposition and re-entrainment
- Transfer into channels
- Channel routing of bed and wash loads
- Routing of sediments through reservoirs
- Landscape evolution with the capability to do multi-decadal simulations

Overland Sediment Transport

- Any number of sediment particles
  - Size
  - Specific gravity
- Sediment detachment
  - Raindrop impact
  - Overland flow limits
- Transport Capacity
  - Kilinc-Richardson
  - Engelund-Hansen
  - Multiple shear stress formulas
- Deposition



Cell to Cell Advection of Suspended Sediments

Overland Erosion Process in GSSHA

- Particles are detached by rainfall impact and overland shear.
- If sufficient transport capacity is available, the eroded particles are transported to adjacent cells by advection.
- Deposition is computed with trap efficiency.
- Transport and deposition by particle size and density.
- Sediments are accounted for using three storages:
    - Parent material
    - Deposited materials
    - Materials in suspension
- Each pool has its own distribution of particles.
- Deposited materials are assumed to erode first, then the parent material.
- Elevations can be adjusted for erosion/deposition.

Factors Affecting Detachment and Transport Capacity

- Soil particle size – finer particles are more erodible.
- Cover conditions – any type of vegetative or manmade cover protects the particles from detachment and transport.
- Management actions – actions taken to prevent erosion, no-till, contour plowing, etc. lesson erosion.
- Erosive forces
    - Rainfall intensity
    - Discharge
    - Land surface or friction slope
    - Shear stress

Detachment by Rain

- Detachment of particles by rainfall is a function of momentum, which is a function of rainfall intensity.
- Rainfall detachment (kg m^{-2} s^{-1}) is calculated as the product of several factors related to:
  - K_I – soil erodiability
  - C_w – correction for water depth
  - C_G – vegetative canopy cover factor
  - C_i – cover-management factor, and
  - M_R – rainfall momentum squared.

$$D_R = K_I C_w C_G C_i M_R$$

Overland Flow Detachment

- Overland flow detaches particles by exerting a shear stress that breaks particle bonds.
- Erosion occurs in rills.
- Within a cell overland flow and rill erosion are assumed uniform, so that calculations are for gross rill erosion.
- Detachment capacity rate (kg m-2·s-1)

$$D_c = a(\tau - \tau_c\ )_r^b (1 - G / T_c)$$

  - a and b are empirical coefficients,
  - τ = the flow shear stress (Pa),
  - τ_{cr} = the critical shear stress,
  - G = the sediment load (kg $\text{m}^{-2}\cdot\text{s}^{-1}$), and
  - T_c = the sediment transport capacity of surface runoff (kg m-2·s-1).

Transport Capacity

- Is the amount of sediment that the flow is capable of moving.
- The flow may not be capable of transporting all of the eroded material.
- The flow may be capable of transporting more than the eroded material.
  - In this case the transport capacity will not be satisfied.

Kilinc-Richardson

- Transport capacity is for bulk particles in suspension. Particles will be transported in relation to fraction in suspension.
- Formulation: $q_s = 25500 q^{2.035} S_f^{1.664} \frac{K}{0.15}$

q_s = sediment unit discharge (ton m^{-1} s^{-1}),

  - q = unit water discharge (m^2 s^{-1}), and
  - S_f = friction slope.
  - The erodibility constant – K is the product of the three factors
    - Soil erodibility factor (0-1) - large stones to fine silt.
    - Cover factor (0-1) – concrete to bare.
    - Crop management factor (0-1) – perfect to none.

Engelund-Hansen

- Transport for individual particle sizes or types

$$G_i = K F_i \frac{0.05 B V^2 h^{3/2} S^{3/2}}{(s-1)^2 D_i \sqrt{g}}$$

  - G_i = the volumetric sediment transport rate of *i*-th size fraction,
  - K = the calibration coefficient (= 1 for standard equation),
  - F_i = the proportion of *i*-th faction in the parent material or deposited layer,
  - B = the width of flow,
  - V = the mean water velocity,
  - h = the flow depth,
  - S = the water surface slope,
  - s = is the specific gravity of *i*-th fraction,
  - g = the gravitational acceleration,
  - D_i = the mean size of *i*-th fraction.
- Appropriate method if particles are from materials other than quarts, i.e. the specific gravity is not approximately 2.65.

Empirical Formulations

- Everaert (1991) conducted flume experiments to attempt to relate the D_{50} (median grain size - µm) and several physical constants to observed unit discharge of sediment (q_s kg m^{-2} s^{-1}) in the flume.
- While he derived many such formulations, we found only four to produce usable results, as transport capacity is implemented in GSSHA.
- One advantage of using these methods is they require no parameter specifications. All parameters are calculated internally as follows.

Effective Stream Power

- Stream Power (N m^{-1} s^{-1})
  - Density
  - Gravity
  - Unit Discharge
  - Friction slope

$$w = \rho g q S_f$$

- Effective Stream Power

$$\Omega = \frac{\omega^{1.5}}{R^{\frac{2}{3}}}$$

- Unit Discharge (kg m^{-1} s^{-1})

$$q_s = 4.6\,10^{-7}\,\Omega^{1.75}\,D_{50}^{-0.56}$$

Unit Stream Power

- Unit Sediment Discharge
- (kg m^{-2} s^{-1})

$$q_s = 0.316\left(S_f Vel\right)^{2.59} D_{50}^{-0.39}$$

D50 in µm

Slope and Unit Discharge

▪ *D50* <33	$q_s = 6.16595 (S_f)^{1.9} q^{1.1}$
▪ 33 < *D50* < 61	$q_s = 10.964 (S_f)^{1.94} q^{1.1}$
▪ 61 < *D50* < 122	$q_s = 9.332 (S_f)^{1.77} q^{1.79}$
▪ 122< *D50* < 190	$q_s = 64.565 (S_f)^{2.96} q^{2.18}$
▪ *D50* > 190	$q_s = 10.964 (S_f)^{1.94} q^{1.1}$

- *D50* in μm

Shear Velocity

- Shear Stress (N m^{-2}) $\tau = \rho g h S_f$
- Shear Velocity (m s^{-1}) $u = \left(\frac{\tau}{\rho}\right)^{0.5}$
- *D50*<33 μ>1.4 $q_s = 0.035\ (u - 1.40)^{2.88}$
- 33<*D50*<61 μ>1.4 $q_s = 0.052\ (u - 1.40)^{2.95}$
- 61<*D50*<122 μ>1.45 $q_s = 0.029\ (u - 1.45)^{3.74}$
- 122<*D50*<190 μ>1.55 $q_s = 0.024\ (u - 1.40)^{4.14}$

μ > 1.8 $q_s = 0.0092\ (u - 1.80)^{5.06}$

D50 in μm

Computation of D50

- *D50* is computed from the material properties in each overland cell. Each cell can/will have a unique distribution of particles and particle sizes that evolves over time as erosion and deposition occur. Assuming a semi-log distribution, the mean diameter is computed as (http://cirp.usace.army.mil/wiki/CMS-Flow_Multiple-sized_Sediment_Transport) :

$$d_k = \exp\left[\ln d_1 + \ln\left(d_N/d_1\right)\frac{k-1}{N-1}\right]$$

Particle Settling

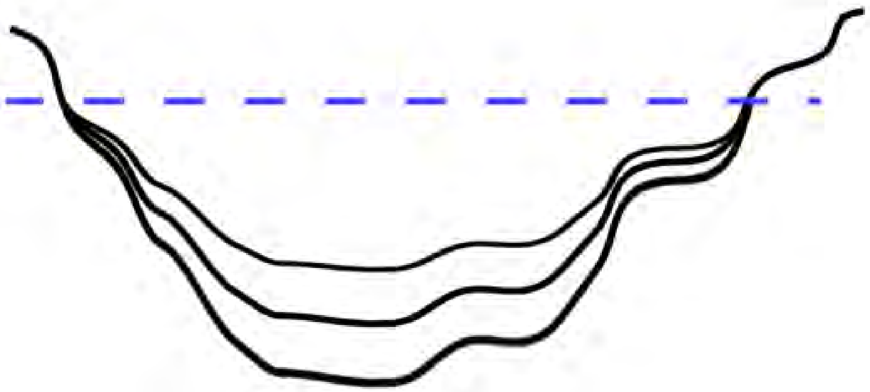
Particle settling is calculated using the trap efficiency (Johnson, 2000) which describes the fraction of each particle size detained in the current cell

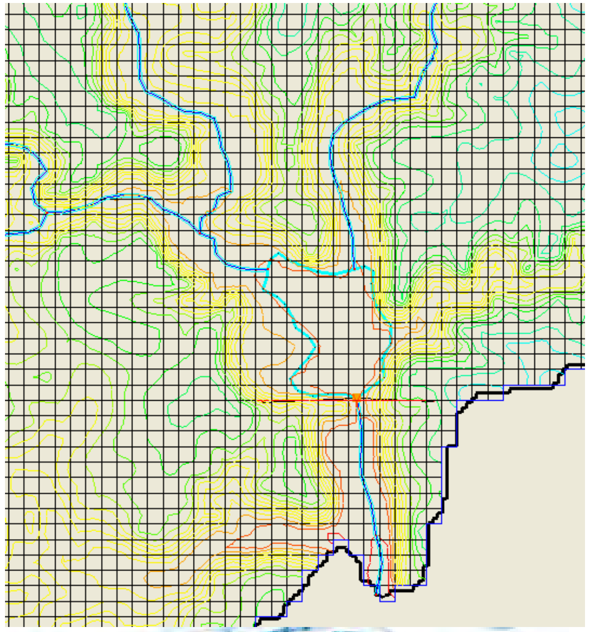
$$T_{Ei} = 1 - e^{\frac{-X\omega_i}{hV}}$$

- T_{Ei} is the trap efficiency for the ith size fraction,
- X is the grid cell size (m),
- ω_i is the fall velocity of the ith size fraction (m s^{-1}),
- h is the overland flow depth (m), and
- V is the overland flow velocity (m s^{-1}).

Sediment in Streams

- Particles larger than sand (user specified) treated as bed load and routed with Yang's method
- Smaller particles treated as wash load – advection dispersion equation
- Stream cross sections adjusted for erosion and deposition
- Particles settle or can be passed through reservoirs





Interaction with Reservoirs

- Sands from overland plane into reservoir are deposited in boundary reservoir cells.
- Sands from upstream channel network are removed from system and accounted for.
- Fines from overland and channels are accounted in reservoir, and can flow through.
- Reservoir is a completely mixed reactor.
- Fines settle in overland cells within the reservoir.
- Fines are discharged at the reservoir outlet.

Interaction with Reservoirs

Terminal velocity

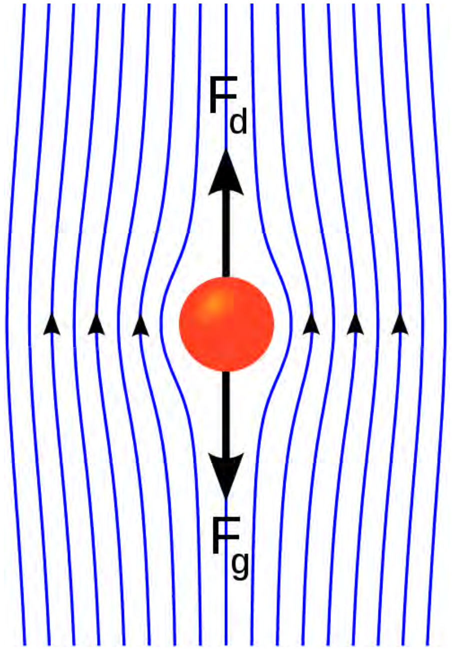
$W = Weight\ \ of\ \ object$

$F_b = Buoyancy\quad force$

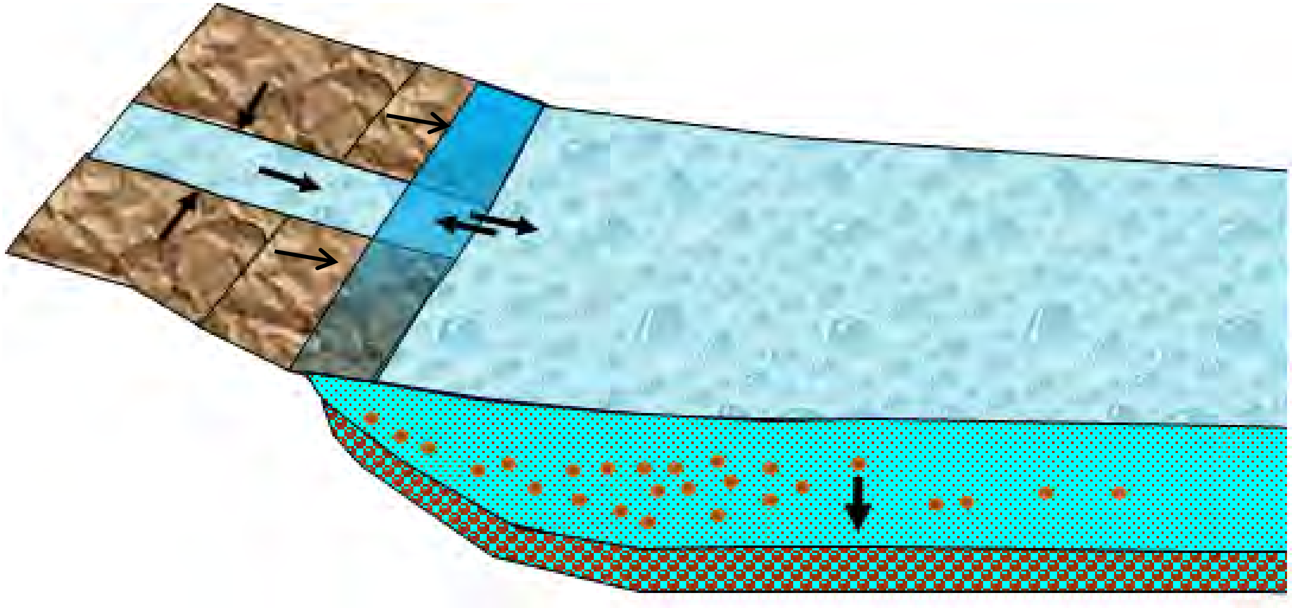
$D = Drag\quad force$

$$W = F_b + D$$

$$V_t[K] = \frac{gd^2}{18\mu(\rho_s - \rho)}$$



$$concentration[k] = \frac{suspended\_volume[k]}{reservoirs\_volume}$$

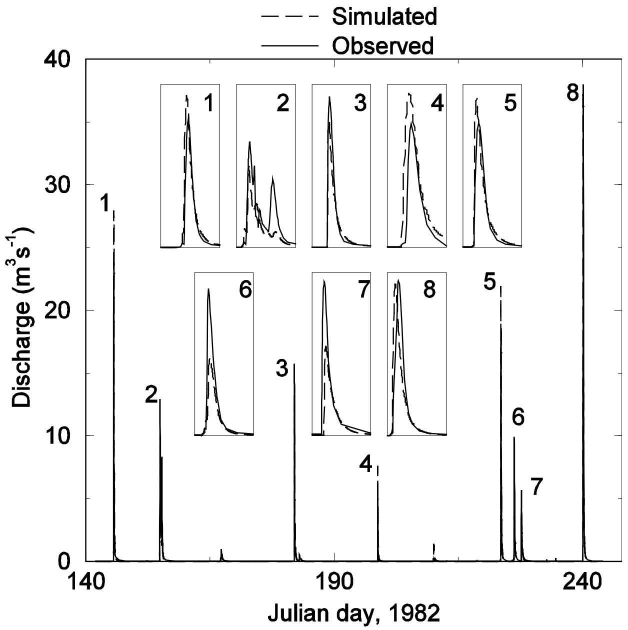


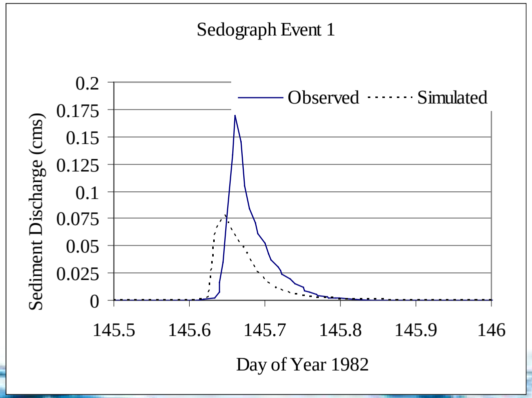
$$settled\_vol[k] = concentration[k] \quad V_t[k] \quad dt \quad reservoir\_area$$

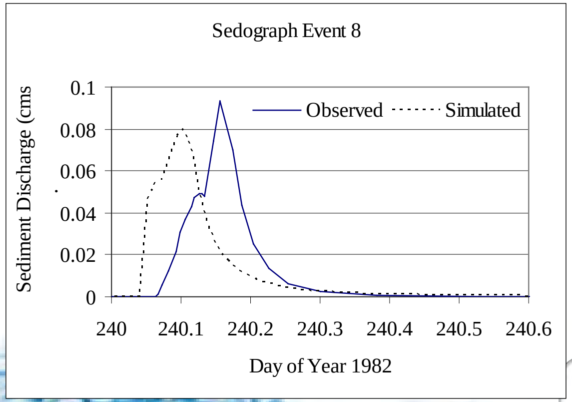
The settled volume is uniformly distributed over all cells currently within the lake.

Continuous Simulations

- Simulates each event with memory of previous events
  - Erosion
  - Deposition
  - Changes in particle distribution
- Simulates events more than 4 orders of magnitude different without change in parameter values







Eau Galle
Sediment Transport

Simulating Sediment Transport

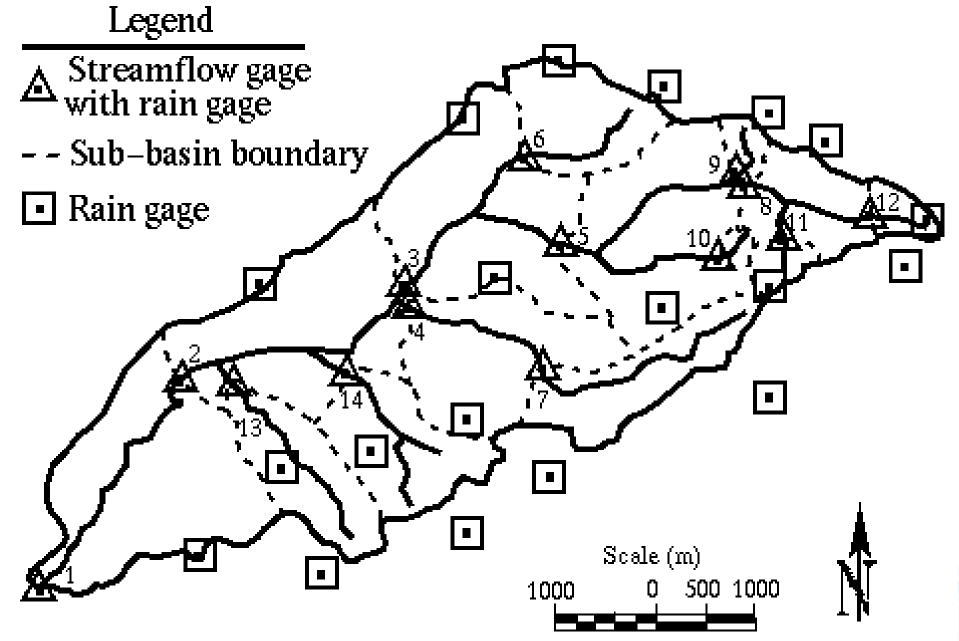
- Select Sediment erosion in the job properties.
- Specify the transport capacity method.
- Specify the distributions of particle sizes and specific gravities.
- Specify the sediment erosion parameters.
  - Index map
  - Mapping table
- Specify the fraction of each particle size in each soil type.
  - Index map
  - Mapping table
- Set the stream erosion parameters.
  - Water temperature
  - Maximum erosion in each stream link
  - Particle size of sand
    - All particles sand size or larger will be treated as bed load
    - All particles smaller than sand size are treated as wash load.

Case Study

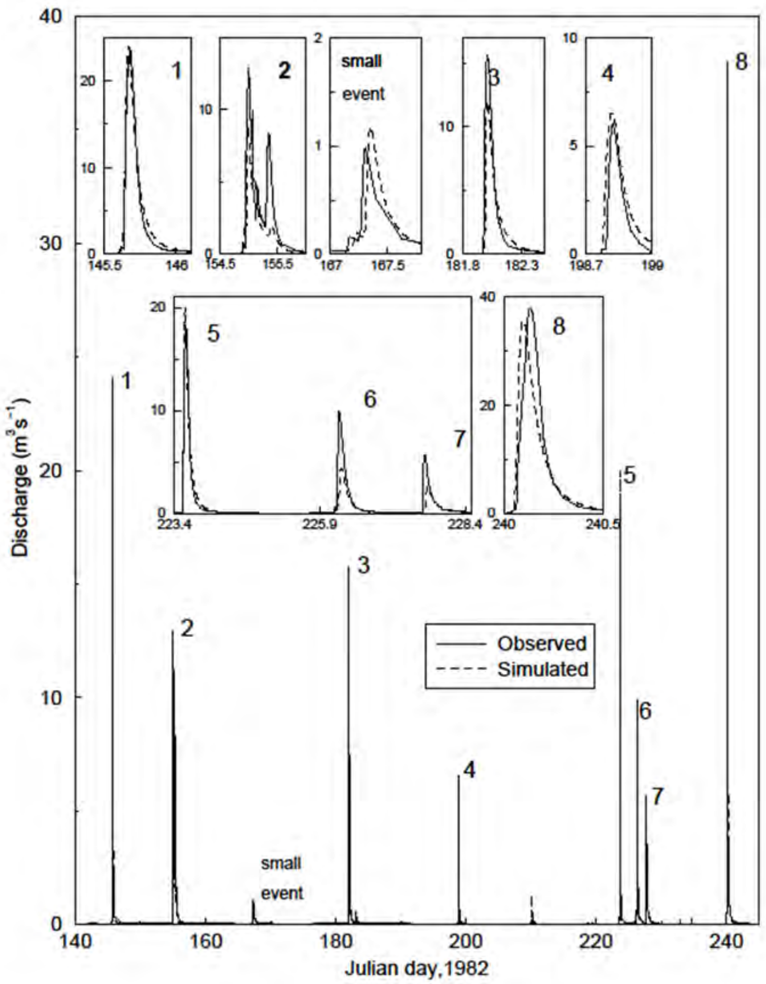
Goodwin Creek Experimental Watershed near Oxford, Mississippi, est. 1981.

Operated by:

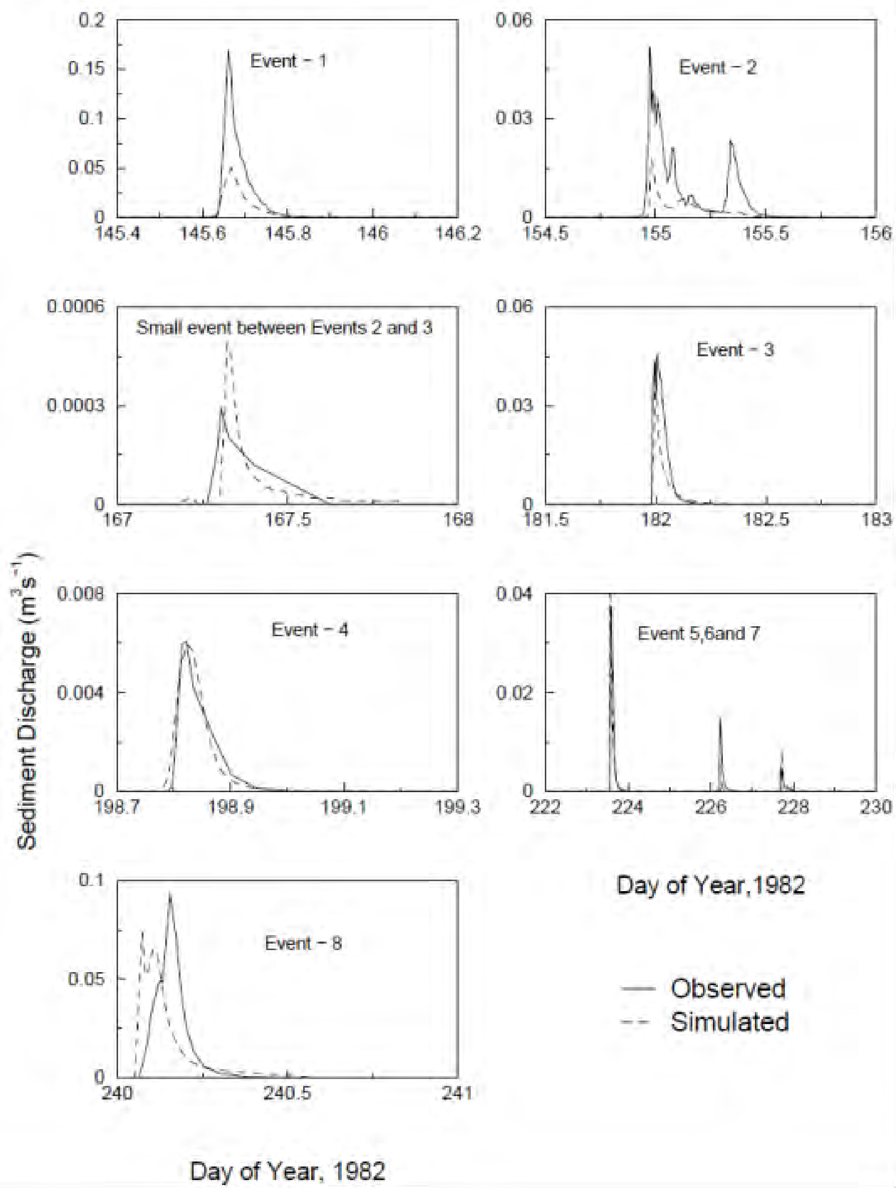
US Dept. of Agriculture, Agricultural Research Service, National Sedimentation Laboratory



GSSHA Model Hydrologic Performance

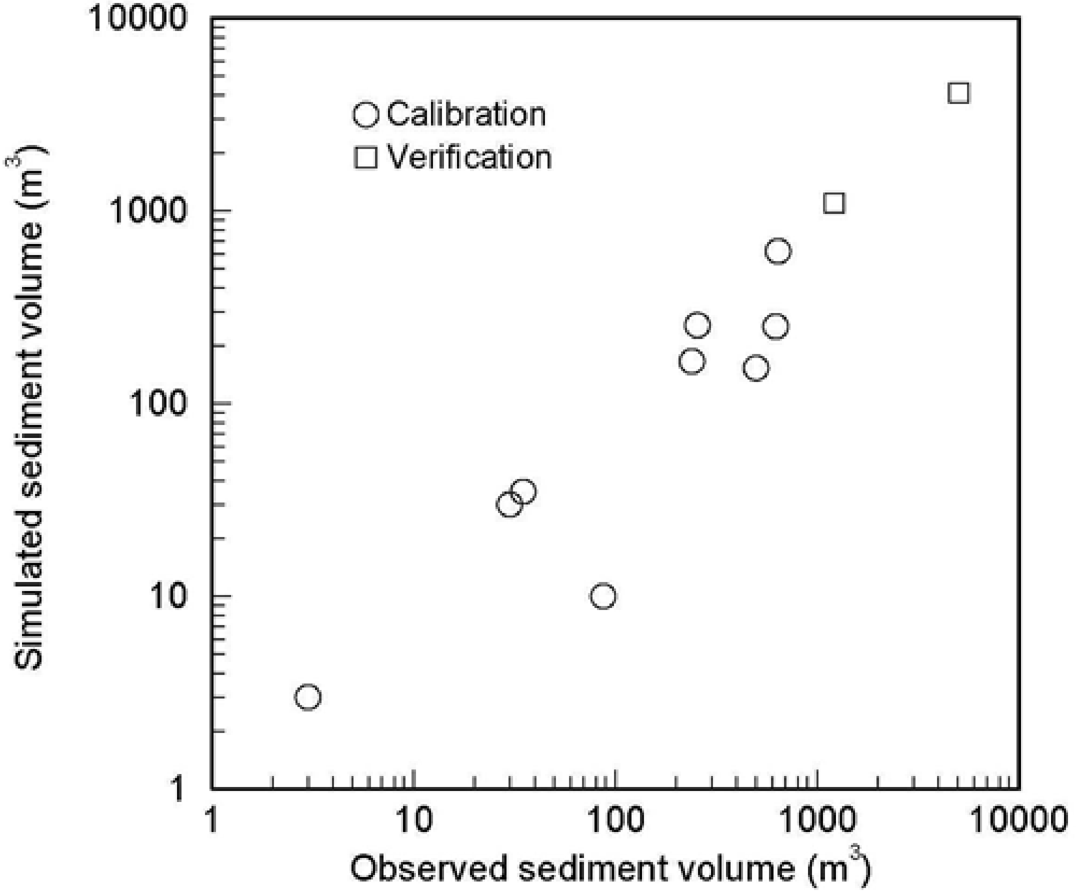


Suspended Sediment Calibration/Verification Results



Extended Calibration/Verification Results

- Included two additional large events in verification period.
- Four orders of magnitude in event size.
- Mean absolute error across all events is 28%.
- No real trend between event size and accuracy.



Recommendations

- If the particle is not silica based, the specific gravity is not 2.65, you must use the England-Hansen equation.
- If you have observed sediment data to calibrate to, use the Kilinc-Richardson equation.
- If you have no observed sediment data to calibrate to, use the slope-unit discharge equation.

Additional Information

- Chapter 10 of the User’s Manual on the GSSHA wiki.
- Downer, C. W., F. L. Ogden, N. R. Pradhan, S. Liu, and A. R. Byrd. 2010. Improved soil erosion and sediment transport in GSSHA. *ERDC TN-SWWRP-10-3*, U.S. Army Engineer Research and Development Center, Vicksburg, MS. https://swwrp.usace.army.mil/
- Downer, C. W., N. R. Pradhan, F. L. Ogden, and A. R. Byrd, 2014. Testing the effects of detachment limits and transport capacity formulation on sediment runoff predictions using the US Army Corps of Engineers GSSHA model. *JHE*, 04014082 1-11, doi: 10.1061/(ASCE)HE.1943-5584.0001104.