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WATERSHED MODELING TOOLS FOR THE CLIMATE CHANGE CHALLENGE

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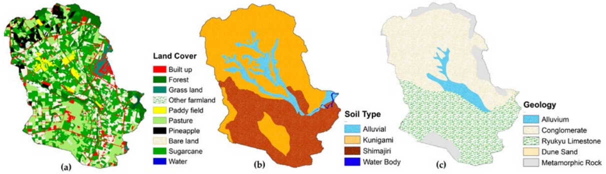
Discussion Overview

For this presentation we will discuss three watershed scale models of varying complexity and capability in regard to general hydrologic/hydraulic capabilities and more specifically erosion and sedimentation capabilities.

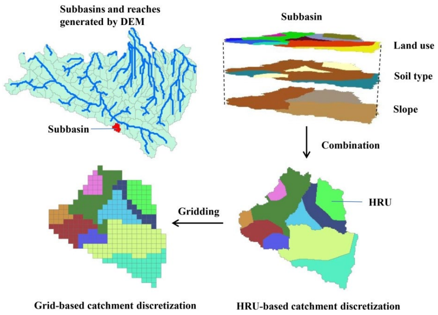
- Gridded Surface Subsurface Hydrologic Analysis (GSSHA) – Fully Distributed
- Soil and Water Assessment Tool (SWAT) – Semi-Distributed
- Hydrologic Simulation Fortran (HSPF) – Lumped Parameter

This discussion is not meant to be all encompassing of available Erosion and Sediment models but rather a selection of models of varying computational fidelity used by the authors to demonstrate the variability of capabilities available to practioners.

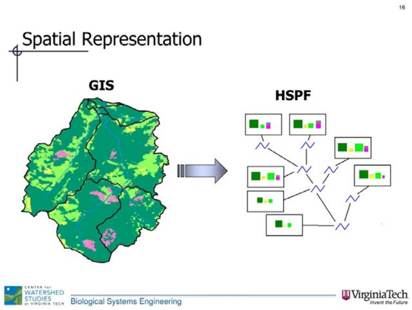
GSSHA



SWAT



HSPF

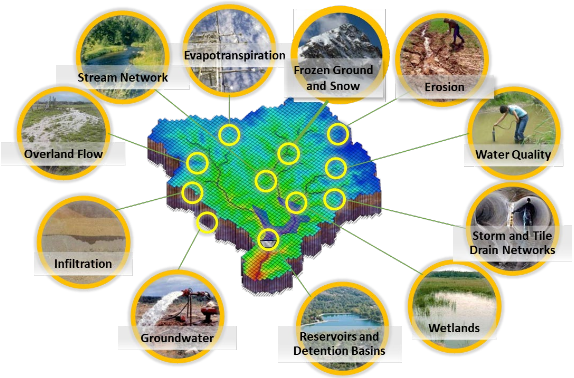


Discussion Overview

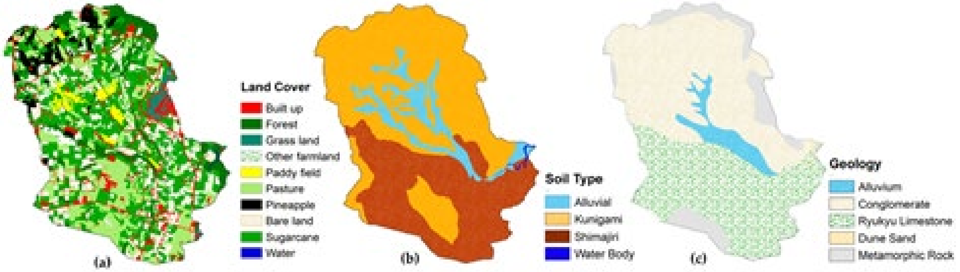
Gridded Surface Subsurface Hydrologic Analysis (GSSHA) is a high fidelity, fine resolution, physically-based, distributed watershed model.

It covers the full hydrologic cycle and simulates processes on a grid cell basis for overland and groundwater.

GSSHA is computationally intensive so is better suited for seasons and design years (e.g. high, medium, and low rainfall intensity annual period of records) and small to medium size watersheds (e.g. acres to a thousand square miles).



- 2D Diffusive Wave Upland Routing
- 1D Diffusive Wave Channel Routing



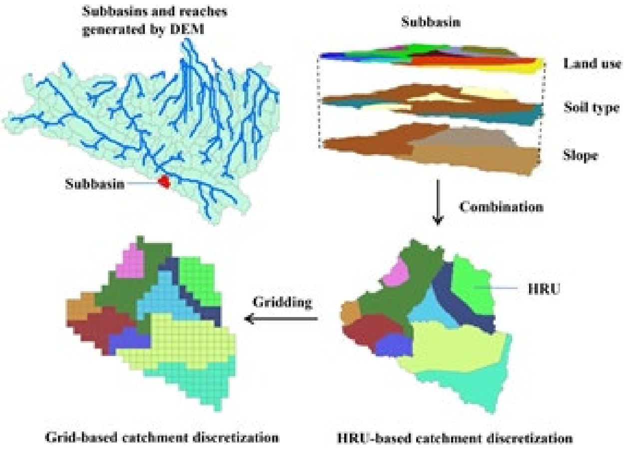
Discussion Overview

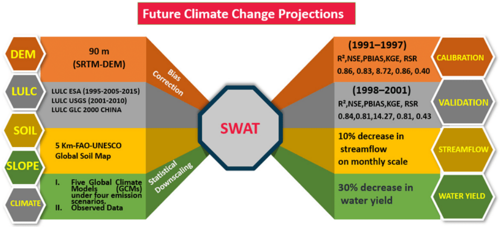
Soil and Water Assessment Tool (SWAT) is a large basin watershed model that is semi-distributed.

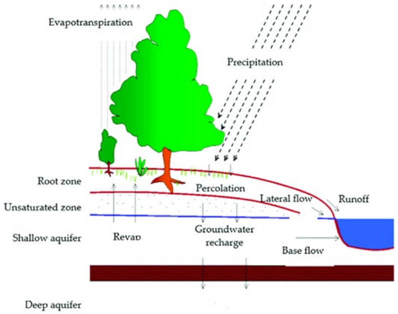
The process simulations can be simulated on a grid basis however the routings are done as lumped routings in the overland and subsurface areas with hydrologic stream routings.

The model is typically executed with a daily time step thus allowing the model to run for decades.

More recent versions of SWAT allow for sub-daily time steps.







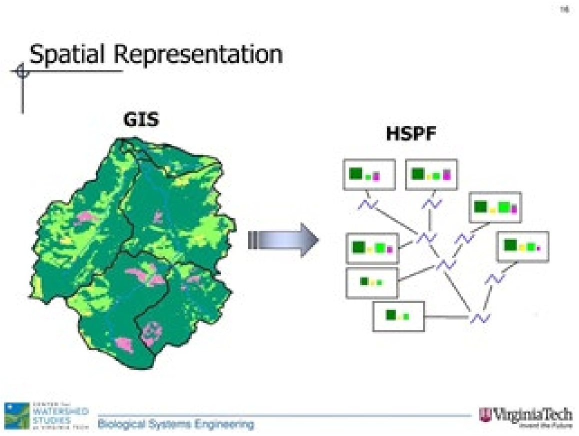
Discussion Overview

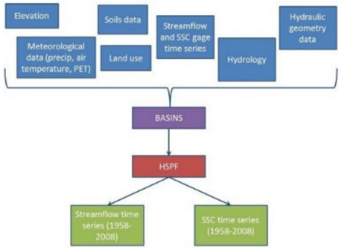
Hydrologic Simulation Program Fortran (HSPF) is a lumped parameter model that simulates the entire hydrologic cycle.

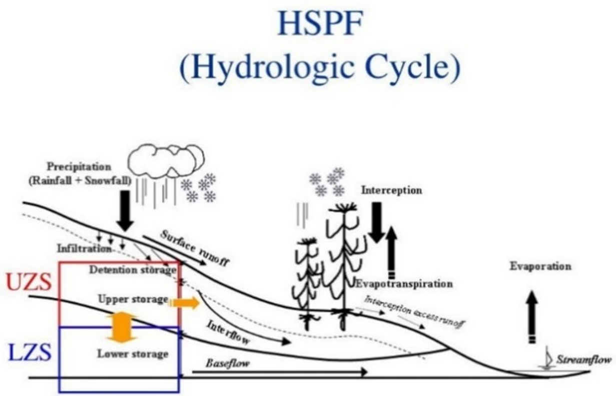
Many process descriptions are empirical in nature and thus require some expertise when modifying the model parameters for future conditions.

The processes are simulated in a lumped parameter manner with hydrologic routing for the streams and fully mixed reservoirs.

HSPF allows sub-daily time steps and is able to run for years to decades.





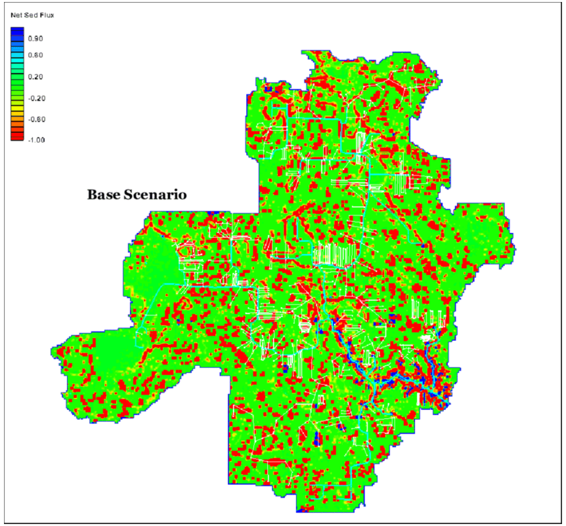


GSSHA

Upland Erosion

The overland sediment routing is based on a two-dimensional mass balance equation (Johnson, 1997),

$$\frac{\partial(hc)}{\partial t} + \frac{\partial(cq_x)}{\partial t} + \frac{\partial(cq_t)}{\partial t} = e(x,y,t) + q_z(x,y,t)$$



where
h = water depth (m);
c = sediment concentration (kg m^{-3});
t = time (s),
q_x and q_y = unit discharge in *x*- and *y*-directions, respectively (m^2/s);
$e(x,y,t)$ = sediment source/sink (kg m^{-2} s^{-1});
$q_z(x,y,t)$=lateral sediment inflow to the channels (m^{-2} s^{-1}).

Detachment of overland sediment particles occurs due to two processes, detachment by <u>rainfall impact</u>, and detachment by <u>surface runoff</u>.

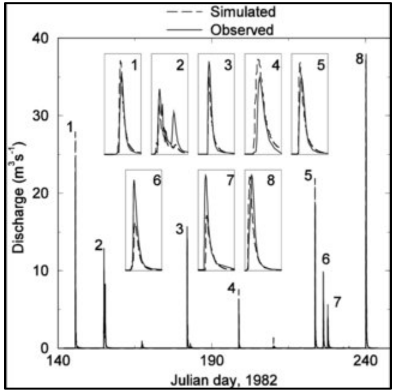
GSSHA
Upland Erosion

The detachment capacity rate, by computational time step, by surface runoff has the form:

$$d_r = a(\tau - \tau_{cr})^b (1 - \frac{G}{T_c})$$

where:
d_r = detachment capacity rate (kg m^{-2} s^{-1}),
a and *b* are empirical coefficients,
τ = the flow shear stress (Pa),
τ_{cr} is the critical shear stress,
G is the sediment load (kg m^{-1} s^{-1}),
T_c is the sediment transport capacity of surface runoff (kg m^{-1} s^{-1}).

- Surface runoff detaches soil particles by exerting a shear stress that breaks the bonds between particles.
- Erosion in rills is lumped and described as gross rill erosion.
- Within a grid cell, rill erosion and flow are assumed to be uniformly distributed.



GSSHA

Upland Erosion

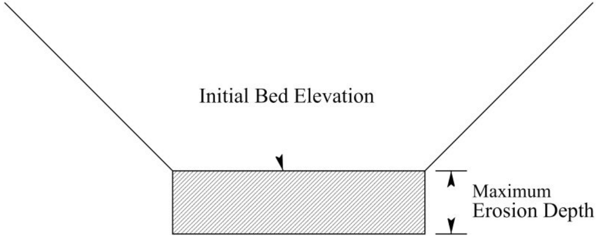
Transport of sediments on the overland flow plane is constrained by the ability of the water to carry sediments.

Several Sediment Transport routines have been implemented in GSSHA:

- Kilinc-Richardson
- Engelund-Hansen
- Stream Power
- Median size diameter, D_{50}

GSSHA

Channel Sedimentation



The Engelund-Hansen (1967) relation is used to calculate sediment transport for each sediment size class and the resulting total transport is calculated by multiplying the proportion of the size in the parent material by the calculated rate.

Several stream power methods (Everaert, 1991) can also be chosen to calculate the transport capacity of surface runoff.

In GSSHA version 5.7 and greater, the Stream Power Approach has been replaced by laboratory physical model empirical equations derived by Everaert (1991), which are based on the sediment particle median size diameter, D_{50}.

GSSHA

Upland Erosion / Channel Sedimentation

When the sediment transport capacity is insufficient to transport the sediment in suspension within a grid cell, sediment is deposited. Sediment deposition in each grid cell/channel reach is calculated for each size fraction using a trap efficiency relationship:

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

where: T_{Ei} is the trap efficiency for the i^{th} size fraction, X is the width of the grid cell/channel (m), W_i is the fall velocity of the i^{th} size fraction (m s^{-1}), h is the overland/channel flow depth (m), and V is the overland/channel flow velocity (m s^{-1}).

The trap efficiency is a number between 0 and 1, which is assumed equal to the fraction of suspended sediment in each size fraction that is deposited in the grid cell. The use of trap efficiency forces larger particles to deposit before smaller particles.

SWAT

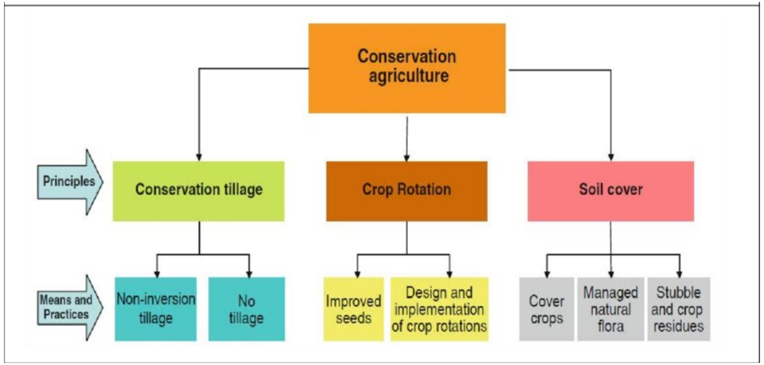
SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large (Basin Scale) complex watersheds with varying soils, land use and management conditions over long periods of time.

SWAT is physically-based rather than incorporating regression equations to describe the relationship between input and output variables.

SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed.

The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc are directly modeled by SWAT using these input data.

SWAT



SWAT has the following features:

- Continuous daily and sub-daily time step, river basin/watershed scale model (physically-based).
- Routes water, sediment, nutrients and pesticides to watershed and basin outlets.
- Predicts impacts of management on water, sediment, and chemical yields.
- Long-term simulations for many decades
- Tracks crop growth, tillage, fertilizer/manure application, nutrient cycling on a daily basis.
- Linked with the Conservation Effects Assessment Project (CEAP) Tool.

SWAT

Overland Sediment Yield

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE), event based, to compute soil erosion at the Hydrologic Response Unit (HRU) level. It uses runoff energy to detach and transport the sediment. MUSLE can be expressed as:

$$Q_s = 11.8(Y * q_{peak} * A)^{0.56} * K * C * P * LS * CF$$

where:

Q_s is the sediment yield in metric tonnes per day
Y is the surface water runoff in mm/ha per day
q_{peak} is peak runoff rate (m^3/s)
A is the area of the HRU (ha)
K is the USLE soil erodibility factor (0.013 metric ton m^2 h/(m^3-metric ton cm))
C is the USLE cover and management factor
P is the USLE support practice factor
LS is the USLE topographic factor
CF is the coarse fragment factor

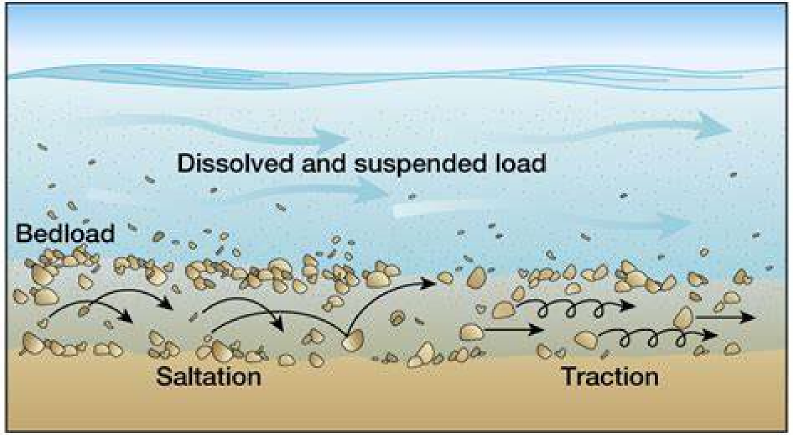
SWAT

Channel Sedimentation

The current version of the SWAT model uses the simplified stream power equation of Bagnold (1977) to route the sediment in the channel.

The maximum amount of sediment that can be transported from a reach segment is function of the peak channel flow velocity.

The sediment routing in the channel consists of channel degradation using stream power and deposition in the channel using fall velocity.



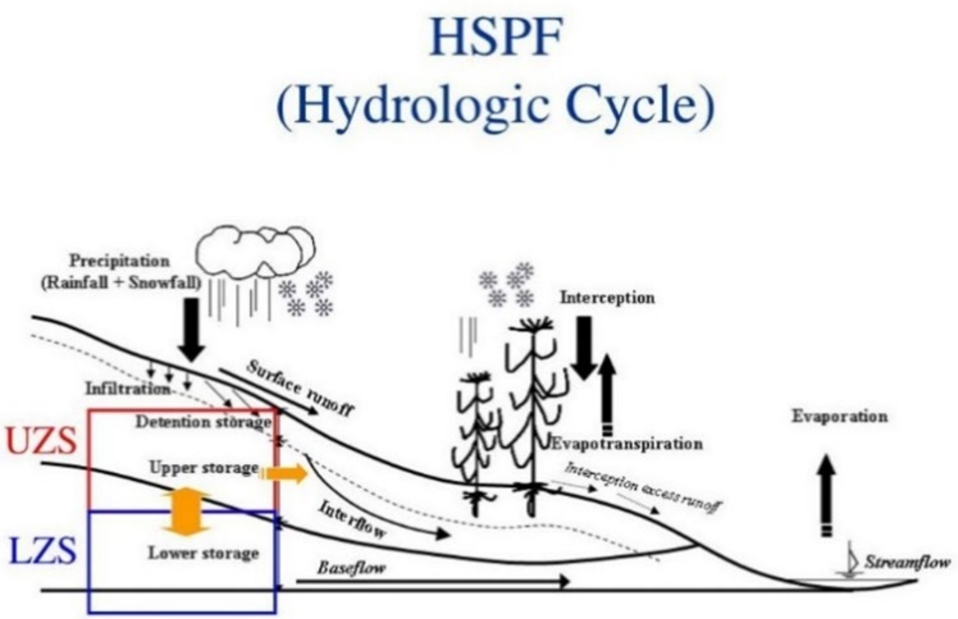
HSPF

HSPF is a comprehensive package for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants.

HSPF incorporates watershed-scale models into a basin-scale analysis framework that includes fate and transport in one dimensional stream channels.

The result of this simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed.

HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical.



HSPF

Estimating Sediment Loadings from the Landscape

Erosion is primarily a function of the amount of soil exposed directly to rainfall and surface runoff, which in turn is affected by rainfall, land cover, land slope, soil disturbance, and transport properties of the soil.

The Universal Soil Loss Equation (USLE), average annual, is an empirical equation commonly used to estimate erosional rates as a function of these factors.

The Universal Soil Loss Equation (USLE)

$$A = R\,K\,L\,S\,C\,P$$

- A = predicted soil loss (tonnes acre^{-1} year^{-1})
- R = erosivity factor
- K = soil erodibility factor
- L = slope length
- S = slope gradient
- C = cover and management factor
- P = erosion control practice factor

L and S: Usually combined as the LS factor

HSPF

Instream Sediment Transport Processes

Since the sediment load from the land surface is calculated in HSPF as a total input, it must be divided into sand, silt, and clay fractions for simulation of instream processes.

Each sediment size fraction is simulated separately, and storages of each size are maintained for both the water column (i.e. suspended sediment) and the bed.

Conclusions

GSSHA is a physically-based distributed watershed model that allows one to simulate flows, sediment, and constituents in 2D across the overland, 1D in the channel, 1D in the vadose zone, and 2D in the groundwater. While GSSHA offers fine temporal and spatial scales it does come at a computational price so the model is best suited for small- to medium-size watersheds for event to year(s) simulations.

SWAT was originally developed to work at a large basin (semi-distributed) and daily time and sub-daily step scale with complex agricultural operations and conservation practices modules. It's strength is in simulating agricultural processes and management/conservation practices.

HSPF was developed from the Stanford Watershed model and incorporated pervious and impervious land segments with sub-surface flow processes. HSPF runs at a sub-daily time step and its strength is in modeling the complete hydrologic cycle for natural and man-made environments (lumped parameters) for years to decades.

Questions

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