SEDIMENT CALIBRATION PROCEDURES AND GUIDELINES FOR WATERSHED MODELING

By

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ABSTRACT

Sediment is one of the most difficult water quality constituents to accurately represent in current watershed and stream models. Important aspects of sediment behavior within a watershed system include loading and erosion sources, delivery of these eroded sediment sources to streams, drains and other pathways, and subsequent instream transport, scour and deposition processes.

Sediment calibration for watershed models involves numerous steps in estimating model parameters and determining appropriate adjustments needed to insure a reasonable simulation of the sediment sources, delivery, and transport behavior within the channel system. Rarely is there sufficient observed local data at sufficient spatial detail to accurately calibrate all parameters for all land uses and each stream and waterbody reach. Consequently, model users focus the calibration on sites with observed data and review simulations in all parts of the watershed to ensure that the model results are consistent with field observations, historical reports, and expected behavior from past experience.

This paper explores a ‘weight of evidence’ approach for sediment calibration as part of overall watershed model calibration, using both graphical and statistical measures, based on recent experience with the U. S. EPA Hydrological Simulation Program - FORTRAN (HSPF). Model parameterization and calibration procedures are described, using sample model results, to demonstrate recommended graphical and statistical procedures to assess model performance for sediment loadings, concentrations, and budgets within a watershed modeling framework. Although the results are specific to the EPA HSPF model, the approach and procedures for sediment calibration are applicable to other watershed models that represent sediment processes and behavior at the watershed scale.

KEYWORDS

HSPF, erosion, sediment delivery, GIS, sediment rating curves, shear stress, TMDL, USLE

INTRODUCTION

Sediment is a primary constituent of concern for many watershed assessments and Total Maximum Daily Load (TMDL) studies being performed across the country. In addition to issues related to sediment impacts on stream habitats, sediment is also a carrier of many other pollutants, including metals, phosphorus, organics, and bacteria. Unlike many other pollutants, eliminating all sediments from the stream is not a solution since that will ultimately lead to channel scour and/or bank failures, as the stream attempts to reach a stable, dynamic equilibrium.

Sediment is also one of the most difficult water quality constituents to accurately represent in current watershed and stream models. Important aspects of sediment behavior within a watershed system include loading and erosion sources, delivery of these eroded sediment sources to streams, drains and other pathways, and subsequent instream transport, scour and deposition processes.

A ‘weight-of-evidence’ approach is rapidly becoming the standard practice in watershed modeling. Model performance and calibration/validation are evaluated through qualitative and quantitative measures, involving both graphical comparisons and statistical tests. For flow simulations where continuous records are available, all these techniques are often employed, and the same comparisons are performed, during both the calibration and validation phases. For water quality constituents, including sediment, model performance is often based primarily on visual and graphical presentations as the frequency of observed data is often inadequate for accurate statistical measures beyond basic metrics (e.g., mean). However, consistency checks with expected value ranges for loading rates and stream morphology and behavior are critical when spatially distributed field data are limited.

This paper explores the ‘weight of evidence’ approach for sediment calibration as part of overall watershed model calibration based on recent experience with the U. S. EPA Hydrological Simulation Program - FORTRAN (HSPF) (Bicknell et al., 2001). Model parameterization and calibration procedures are described, using example applications and sample model results, to demonstrate recommended graphical and statistical procedures used to assess model performance for sediment loadings, concentrations, and budgets within a watershed modeling framework. Although the results are specific to the EPA HSPF model, the approach and procedures for sediment calibration are applicable to other watershed models that represent sediment processes and behavior at the watershed scale.

SEDIMENT CALIBRATION OVERVIEW

Sediment calibration follows the hydrologic calibration and must precede water quality calibration. Calibration of the parameters involved in simulation of watershed sediment erosion is more uncertain than hydrologic calibration due to less experience with sediment simulation in different regions of the country. The process is analogous; the major sediment parameters are modified to increase agreement between simulated and recorded monthly sediment loss and storm event sediment removal. However, observed monthly sediment loss is often not available, and the sediment calibration parameters are not as distinctly separated between those that affect monthly sediment and those that control storm sediment loss. In fact, annual sediment losses are often the result of only a few major storms during the year.

Sediment calibration for watershed models involves numerous steps in estimating model parameters then determining appropriate adjustments needed to ensure a reasonable simulation of the sediment sources, delivery, and transport behavior within the channel system. These steps usually include:

1. Estimating target (or expected) sediment loading rates from the landscape, often as a function of topography, land use, and management practices
2. Calibrating the model loading rates to the target rates
3. Adjusting scour, deposition and transport parameters for the stream channel to mimic expected behavior of the streams/waterbodies
4. Analyzing sediment bed behavior (i.e. bed depths) and transport in each channel reach as compared to field observations
5. Analyzing overall sediment budgets for the land and stream contributions, along with stream aggrading and degrading behavior throughout the stream network
6. Comparing simulated and observed sediment concentrations, including particle size distribution information, and load information where available
7. Repeating steps 1 through 6 as needed to develop a reasonable overall representation of sediment sources, delivery, and transport throughout the watershed system

Rarely is there sufficient observed local data at sufficient spatial detail to accurately calibrate all parameters for all land uses and each stream and waterbody reach. In fact, for sediment modeling, users are often limited to observed data for monthly or storm periods at only selected sites within the watershed. Consequently, model users focus the calibration on those sites with observed data, and then must review simulations in all parts of the watershed to ensure that the model results are consistent with field observations, historical reports, and expected behavior from past experience. This is especially critical for sediment modeling due to the extreme dynamic behavior of sediment erosion and transport processes.

Below we journey through each of the above steps to provide model users with general guidance and recommendations for modeling watershed-scale sediment processes in a logical and reasonable fashion. Although the specific parameter definitions and discussions and sample model results are based on the HSPF model, the overall procedures should prove useful to users of other watershed scale sediment model codes.

SEDIMENT EROSION CALIBRATION

Sediment loadings to the stream channel are estimated by land use category from literature data, local Extension Service sources, or procedures like the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and then adjusted for delivery to the stream with estimated sediment delivery ratios (SDRs). This delivery adjustment is needed because HSPF, like most watershed-scale (lumped parameter) models, represents landscape loadings to the stream channel, which are less than the field-scale estimates from USLE. These estimated loading rates then become ***'calibration targets'*** for the watershed model.

Model parameters are then adjusted so that model-calculated loadings are consistent with these estimated ***'calibration targets'*** and loading ranges. The model-calculated loadings are further evaluated in conjunction with the instream sediment transport calibration (discussed below) that extend to a point in the watershed where sediment concentration and/or load data are available.

The objective is to represent the overall sediment behavior of the watershed, with knowledge of the morphological characteristics of the stream (i.e. aggrading or degrading behavior), using sediment loading rates that are consistent with the ***calibration targets*** and modeled concentrations that provide a reasonable match with instream sediment data.

Step 1: Estimating Sediment Loadings from the Landscape

Sediment concentrations measured at a particular gage reflect the combined affects of nonpoint source contributions from multiple land uses, any point sources upstream from the gage, and instream processes (e.g., deposition, scour, bank erosion). Consequently, the ***calibration target*** sediment loading rates need to be developed to help guide the calibration effort and ensure that the simulated erosional rates from each land use category are reasonable, and thereby provide a sound basis for calibrating the instream processes.

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 USLE is an empirical equation commonly used to estimate erosional rates as a function of these factors. The USLE formula is expressed as follows:

$$A = R * K * L * S * C * P$$

A = annual soil loss in tons per acre per year
R = rainfall erosivity factor
K = soil erodibility factor
L = slope length factor
S = slope gradient factor
C = cover management factor
P = erosion control practice factor

The ***R factor*** *is* typically obtained from a national or regional isoerodent map, readily available in many soil engineering handbooks (e.g. Renard et al, 1997), and accounts for the amount and intensity of rainfall and runoff typical of a region.

The ***K factor*** is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. Texture is the principal factor affecting ***K***, but structure, organic matter and permeability also contribute. Determining ***K*** values can be performed either from handbook tables, or acquisition of accurate geo-spatial soils data from the U.S. Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS) if a GIS approach is employed. The most common forms of these data are the STATSGO and SSURGO databases and/or GIS coverages.

The ***L factor*** is very closely associated with the ***S factor***, where ***S*** is the slope gradient factor and the ***L*** is the length of that slope. The USLE was created to predict soil erosion delivered to the base of a 22-meter agricultural plot with a uniform slope of 9 percent. The ***S*** and ***L factors*** are typically combined, defined as the topographic factor ***LS,*** to account for site specific conditions relative to the standard plot.

The ***C factor*** is the crop/vegetation and management factor. It is used to determine the relative effectiveness of soil and crop management system or vegetation in terms of preventing soil loss. The C factor is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land.

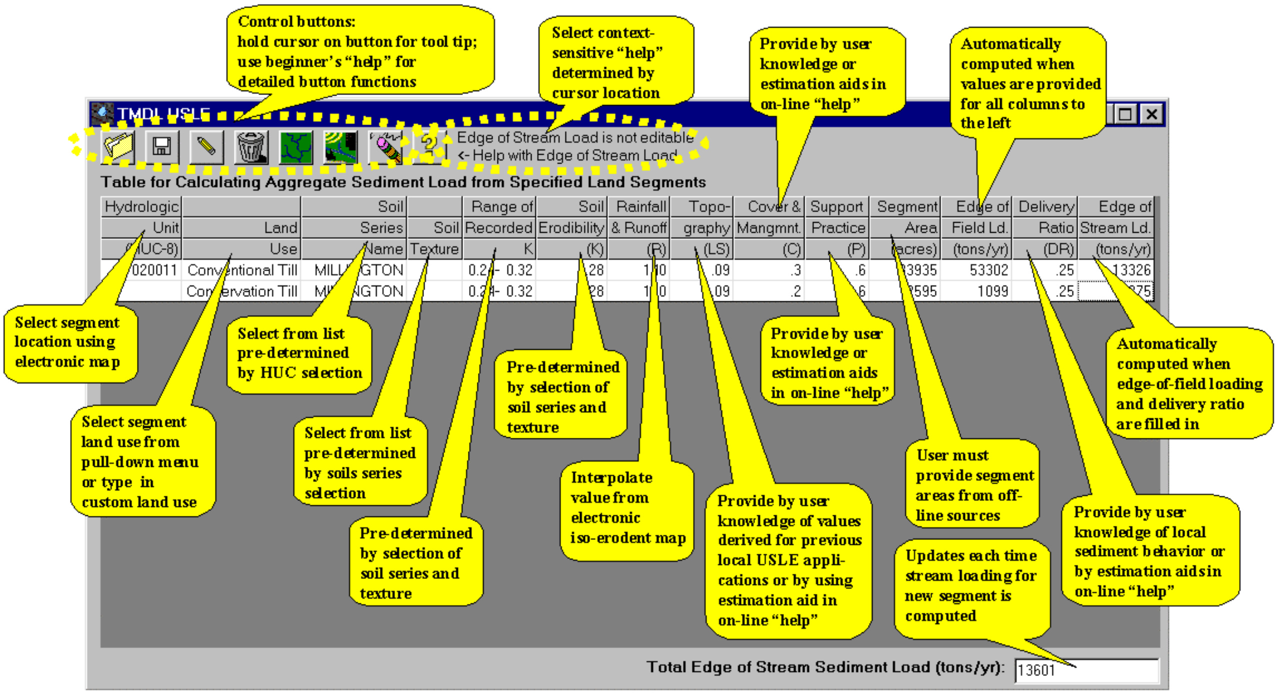
The ***P factor*** is the support practice factor and reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. The factor represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. The most commonly used supporting cropland practices are cross slope cultivation, contour farming, and strip cropping. In cases where the conservation practice factor is not relevant, it is set as 1.0 for all areas, which does not negatively or positively influence the output of the model.

As the USLE was developed at a field scale, depositional processes that occur in overland flow prior to reaching a stream channel are not included. Therefore, it is necessary to reduce the gross erosion by a fraction. This fraction or portion of sediment that is available for delivery is referred to as the Sediment Delivery Ratio (SDR). This ratio is then multiplied by the predicted or gross erosion rate to estimate the percent of eroded material to reach a specific point or location (e.g., outlet, waterbody, channel). There is no generally accepted procedure to estimate the SDR, which is affected by numerous factors including sediment source, texture, nearness to the stream, channel density, basin area, slope, land use/cover, and rainfall-runoff factors; however, several empirical formulas exist (e.g. see Greenfield et al., 2002).

Under EPA funding, AQUA TERRA Consultants developed a Visual Basic spreadsheet tool named TMDL USLE (Hummel et al., 2000) for use in sediment associated TMDL studies (http://www.epa.gov/ceampubl/swater/usle/index.htm). This spreadsheet is useful for estimating the expected relative magnitude of land surface sediment loadings (tons per year) from different land use types within a watershed, and thereby can be used to develop sediment calibration targets for watershed models. Maps, recommended value tables for USLE factors, and other information useful in deriving appropriate values for the USLE and delivery ratios are provided, to the extent that it is practical, throughout the U.S. The tool includes an on-line tutorial and active links to Internet web sites containing supplemental information that can assist users in evaluating USLE factors.

Figure 1 shows the computation screen for the TMDL USLE program, with highlighted comment ‘bubbles’ identifying the source of values and information in each cell.

As an alternative to a spreadsheet based approach, using a GIS platform allows the USLE to be applied on a cell-by-cell basis, using watershed specific information, for a more spatially accurate use of the equation and model land use specific estimates of erosional rates. The USLE can be applied in a grid-based GIS environment where map algebra can be performed with the GIS layer values.



Edge of Stream Load is not editable
<- Help with Edge of Stream Load

Table for Calculating Aggregate Sediment Load from Specified Land Segments

Hydrologic Unit (HUC-8)	Land Use	Soil Series Name	Soil Texture	Range of Recorded K	Soil Erodibility (K)	Rainfall & Runoff (R)	Topo-graphy (LS)	Cover & Mangmnt. (C)	Support Practice (P)	Segment Area (acres)	Edge of Field Ld. (tons/yr)	Delivery Ratio (DR)	Edge of Stream Ld. (tons/yr)
020011	Conventional Till	MILL GTON		0.2 - 0.32	28	1 0	.09	.3	.6	3935	53302	.25	13326
	Con ervation Till	M NGTON		0.2 - 0.32	28	1 0	.09	.2	6	595	1099	.25	75

Total Edge of Stream Sediment Load (tons/yr): 13601

Control buttons:
hold cursor on button for tool tip;
use beginner's "help" for
detailed button functions

Select context-
sensitive "help"
determined by
cursor location

Provide by user
knowledge or
estimation aids in
on-line "help"

Automatically
computed when
values are provided
for all columns to
the left

Select segment
location using
electronic map

Select segment
land use from
pull-down menu
or type in
custom land use

Select from list
pre-determined
by HUC selection

Select from list
pre-determined
by soils series
selection

Pre-determined
by selection of
soil series and
texture

Pre-determined
by selection of
soil series and
texture

Interpolate
value from
electronic
iso-erodent map

Provide by user
knowledge of values
derived for previous
local USLE appli-
cations or by using
estimation aid in
on-line "help"

Provide by user
knowledge or
estimation aids
in on-line "help"

User must
provide segment
areas from off-
line sources

Updates each time
stream loading for
new segment is
computed

Automatically
computed when
edge-of-field loading
and delivery ratio
are filled in

Provide by user
knowledge of local
sediment behavior or
by estimation aids in
on-line "help"

below.

$$\mathbf{LS = [0.065 + 0.0456(slope) + 0.006541(slope)^2\,] * [resolution / normlength]^{\,n}}$$

slope = slope steepness (%)
resolution = cell resolution (meters or feet)
normlength = 72.5 ft or 22.1 meters
n = function of slope (see table below)

slope	< 1	1 $\leq$ slope < 3	3 $\leq$ slope < 5	> 5
n	0.2	0.3	0.4	0.5

The ***K factor*** can be obtained from a descriptor or attribute, referred to as *'kffac*t' within the STATSGO or SSURGO databases. The attribute *'kffac*t' defines the soil erodibility factor that is fragment free for use in the USLE.

Within a GIS, the SDR can be calculated in a manner to try and account for all the aforementioned controlling factors, or in a simplified manner based on the drainage area of the channel segment as defined by the model setup. This simple approach is referred to as a watershed area-based method. The equation below was converted from a curve presented in the National Engineering Handbook produced by the Soil Conservation Service in 1983 (USDA-NRCS, 1983).

$$\mathbf{SDR = 0.417762 * A^{-0.134958} - 0.127097}$$

A = drainage area (sq. miles)

Numerous additional empirical formulas exist, including formulas and tables provided within the TMDL USLE tool. Ultimately, once the gross erosional rates are adjusted by the SDR, it is possible to use the GIS to summarize the range of erosional rates on a model land use specific basis. Figure 2 graphically depicts the process of taking the input data (i.e., DEM, soils, land use/cover), calculating USLE factors, and developing estimates of the erosional rates.

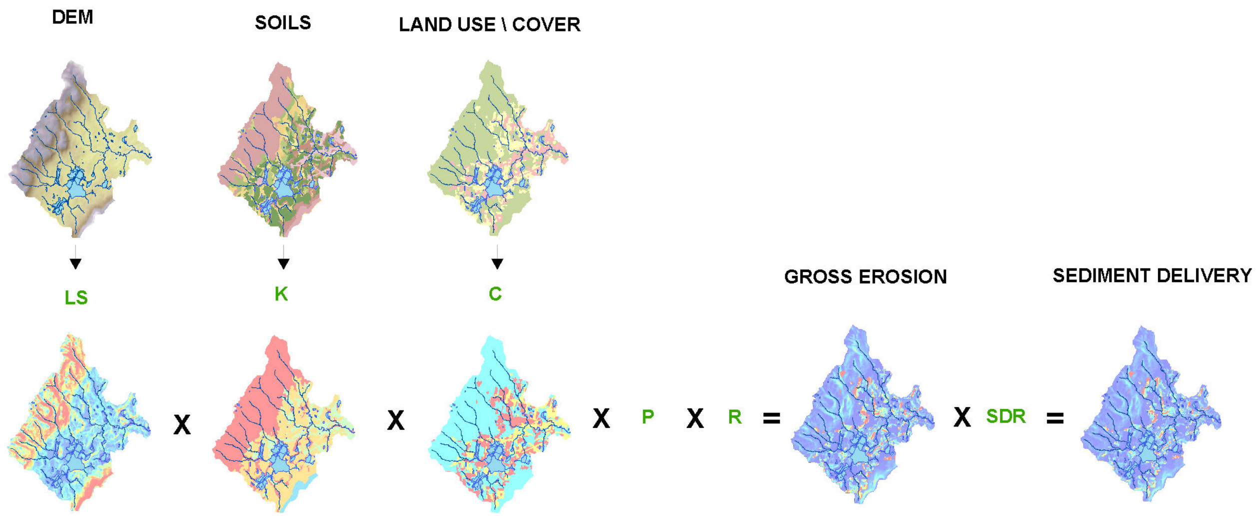


Figure 2 – GIS Framework for USLE

Calibration targets developed from the TMDL USLE spreadsheet, a GIS-based approach, or other procedures should be used only to define approximate ranges of loading rates to help guide the calibration for the watershed or region of concern. There will often be extreme variation in the calculated rates from year to year, and site to site, and users should only expect that the model rates will be ***consistent with*** the targets, not necessarily ***equal to*** them. Table 1 shows typical ranges of sediment loading rates for various land categories.

Table 1 - Typical Ranges of Expected Erosion Rates

	Tons/ac	**Tonnes/ha**
Forest	0.05 - 0.4	0.1 - 0.9
Pasture	0.3 - 1.5	0.7 - 3.4
Conventional Tillage	1.0 - 7.0	2.2 - 15.7 (crop dependent)
Conservation Tillage	0.5 - 4.0	1.1 - 9.0 (crop dependent)
Hay	0.3 - 1.8	0.7 - 4.0
Urban	0.2 - 1.0	0.4 - 2.2
Highly Erodible Land	> ~ 15.0	> ~ 33.6

Step 2: Sediment Erosion Calibration

Each of the calibration steps identified in the overall procedures involve first a parameterization component followed by the actual calibration, or parameter adjustment, component to improve agreement between model values and various field observations. Clearly, the specific parameters to adjust for soil erosion calibration will depend on the specific model being used. In HSPF, the erosion process on pervious land areas is represented as the net result of detachment of soil particles by raindrop impact on the land surface, and then subsequent transport of these fine particles by overland flow. On impervious surfaces (e.g. parking lots, driveways), soil splash by raindrop impact is neglected and solids washoff is often controlled by the rate of accumulation of solid materials. The primary sediment erosion solids parameters are as follows:

KRER - Coefficient in soil detachment equation (pervious areas)
KSER - Coefficient in sediment washoff equation (pervious areas)
KEIM - Coefficient in impervious area solids washoff equation
ACCSDP - Accumulation rate of solids on impervious surfaces

Although a number of additional parameters are involved in sediment erosion and solids calibration, such as those related to vegetal cover, agricultural practices, rainfall and overland flow intensity, etc., KRER and KSER are the primary ones controlling sediment loading rates. KRER is usually estimated as equal to the erodibility factor, K, in the USLE (noted above), and then adjusted in calibration, while KSER is primarily evaluated through calibration and past experience. For impervious surfaces, the rate of washoff is controlled by the KEIM parameter, but the net washoff is most often limited by the accumulation rate, ACCSDP. Table 2 lists the sediment and solids washoff parameters in HSPF, along with typical and possible minimum and maximum ranges based on application experience over the past 20 years. In addition, the HSPFParm database (U. S. EPA, 1999) provides calibrated parameter values for numerous watersheds across the US.

In general, sediment calibration involves the development of an approximate equilibrium or balance between the accumulation and generation of sediment particles on one hand and the washoff or transport of sediment on the other hand. Thus, the accumulated sediment on the land surface should not be continually increasing or decreasing throughout the calibration period. Extended dry periods will produce increases in surface sediment accumulations, and extended wet periods will produce decreases. However, the overall trend should be relatively stable from year to year. This equilibrium must be developed on both pervious and impervious surfaces, and must exist in conjunction with the accurate simulation of monthly and storm event sediment loss, depending on the data available for calibration. Additional guidance in sediment erosion calibration is provided in the HSPF Application Guide (Donigian et al., 1984).

Table 2 - Value Ranges for HSPF Sediment Erosion and Solids Washoff Parameters

			RANGE OF VALUES					
NAME	DEFINITION	UNITS	TYPICAL		POSSIBLE		FUNCTION OF ...	COMMENT
			MIN	MAX	MIN	MAX		
SED - PARM2								
SMPF	Management Practice (P) factor from USLE	none	0.0	1.0	0.0	1.0	Land use, Ag practices	Use P factor from USLE
KRER	Coefficient in the soil detachment equation	complex	0.15	0.45	0.05	0.75	Soils	Estimate from soil erodibility factor (K) in USLE
JRER	Exponent in the soil detachment equation	none	1.5	2.5	1.0	3.0	Soils, climate	Usually start with value of 2.0
AFFIX	Daily reduction in detached sediment	per day	0.03	0.10	0.01	0.50	Soils, compaction, ag operations	Reduces fine sediments following tillage
COVER	Fraction land surface protected from rainfall	none	0.0	0.90	0.0	0.98	Vegetal cover, land use	Seasonal/monthly values often used
NVSI	Atmospheric additions to sediment storage	lb/ac-dy	0.0	5.0	0.0	20.0	Deposition, activities, etc.	Can be positive or negative
SED - PARM3								
KSER	Coefficient in the sediment washoff equation	complex	0.5	5.0	0.1	10.0	Soils, surface conditions	Primary sediment **Calibration** parameter
JSER	Exponent in the sediment washoff equation	none	1.5	2.5	1.0	3.0	Soils, surface conditions	Usually use value of about 2.0
KGER	Coefficient in soil matrix scour equation	complex	0.0	0.5	0.0	10.0	Soils, evidence of gullies	**Calibration**, only used if there is evidence of gullies
JGER	Exponent in soil matrix scour equation	none	1.0	3.0	1.0	5.0	Soils, evidence of gullies	Usually use value of about 2.5
SLD – PARM2								
KEIM	Coefficient in the solids washoff equation	complex	0.5	5.0	0.1	10.0	Surface conditions, solids charac.	Primary solids **Calibration** parameter
JEIM	Exponent in the solids washoff equation	none	1.0	2.0	1.0	3.0	Surface conditions, solids charac.	Usually use value of about 1.5
ACCSDP	Solids accumulation rate on the land surface	lb/ac-dy	0.0	2.0	0.0	30.0	Land use, traffic, human activities	**Calibration**, primary source of solids from impervious areas
REMSDP	Fraction of solids removed per day	per day	0.03	0.2	0.01	1.0	Street sweeping, wind, traffic	Usually start with value of about 0.05, and calibrate

INSTREAM SEDIMENT TRANSPORT CALIBRATION

Parameterization of Instream Sediment Transport Processes

Once the sediment loading rates are calibrated to provide the expected input to the stream channel, the sediment calibration then focuses on the channel processes of deposition, scour, and transport that determine both the total sediment load and the outflow sediment concentrations to be compared with observations. In practice, instream calibration involves steps 3, 4 and 5 as listed and discussed above; these steps involve both initial parameterization, to establish initial parameter values, and a subsequent adjustment process. For HSPF, the initial parameterization includes the following:

- Divide input sediment loads into appropriate size fractions
- Estimate initial parameter values and storages for all reaches
- Run HSPF to calculate shear stress in each reach to estimate critical scour and deposition values

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.

Fractionating the Eroded Material

The eroded material is fractionated into sand, silt, and clay prior to entering a model reach using available soils information; typically, a single fractionation scheme is used for all reaches. However, if the resolution of the data and spatial diversity of the soils warrant alternate schemes, it is possible for each reach to use separate fractions. The fractions should reflect the relative percent of the surface material (i.e., sand, silt, clay) available for erosion in the surrounding watershed, but also should include an enrichment factor of silt and clay to represent the likelihood of these finer materials reaching the channel. Thus, the sand particles are more likely to be deposited in the overland flow plane, in swales, ditches, depressions, etc. and therefore the sand would be somewhat transport limited, compared to the silt and clay. For example, if surface soils demonstrate a 40/50/10 distribution for sand/silt/clay, the fractionation for input to the reach might be 15/55/30. Investigation of the bed material composition will also help to provide insight into appropriate fractionation values.

Estimate Initial Parameter Values And Storages For All Reaches

For HSPF, initial sediment parameters, such as particle diameter, particle density, settling velocity, bed depth and composition, and beginning calibration parameter values can be evaluated from local/regional data, past experience, handbook values, etc., and then adjusted based on available site specific data and calibration. Bed composition data are especially important so that the model results can be adjusted to reflect localized aggredation (deposition) or degradation (scour) conditions within the stream system.

In HSPF, the value of bed depth represents the amount of material (calculated from input values for bed width and porosity) that can be scoured from the stream reach; in effect it provides a limit so that the model will inform the user, through a warning message, when the channel has been completely scoured so that the user can make appropriate parameter changes if needed. We often set initial bed depths to 2.0 to 5.0 feet for the natural (i.e. non-channelized) stream segments, and 0.5 to .05 feet for the channelized segments to allow a reasonable amount of scour in the upstream natural channel and limit the scour to scattered localized deposits in channelized sections.

Setting Initial Critical Scour and Depositional Shear Stresses

In HSPF, the transport of the **sand (non-cohesive) fraction** is commonly calculated as a power function of the average velocity in the channel reach in each timestep. This transport capacity is compared to the available inflow and storage of sand particles; the bed is scoured if there is excess capacity to be satisfied, and sand is deposited if the transport capacity is less than the available sand in suspension within the channel reach. For the **silt and clay (cohesive) fractions**, shear stress calculations are performed by the hydraulics (HYDR) module and are compared to user-defined critical, or threshold, values for deposition and scour for each size. When the shear stress for a timestep is greater than the critical value for scour, the bed is scoured at a user-defined erodibility rate; when the shear stress is less than the critical deposition value, the silt or clay fraction deposits at a settling rate input by the user for each size. If the calculated shear stress falls between the critical scour and deposition values, the suspended material is transported through the reach. After all scour and/or deposition fluxes have been determined, the bed and water column storages are updated and outflow concentrations and fluxes are calculated for each timestep. These simulations are performed by the SEDTRN module in HSPF, complete details of which are provided in the HSPF User Manual (Bicknell et al., 2001).

In HSPF, if the model reach being simulated is a stream or river, the bed shear stress is determined as a function of the slope and hydraulic radius of the reach, as follows:

TAU = SLOPE*GAM*HRAD

where:
TAU = stream bed shear stress (lb/ft2 or kg/m2)
SLOPE = slope of the RCHRES (-)
GAM = unit weight, or density, of water (62.4 lb/ft3 or 1000 kg/m3)
HRAD = hydraulic radius (ft or m)

The hydraulic radius is calculated as a function of average water depth (AVDEP) and mean top width (TWID):

HRAD = (AVDEP*TWID)/(2.*AVDEP + TWID)

Average depth is computed as: AVDEP = VOL/SAREA

The mean top width is found using: TWID = SAREA/LEN

where:
LEN = length of the RCHRES, supplied by the user

If the stream reach is a lake, alternative methods are used for the shear calculations (see Users Manual for details).

In HSPF, the hydraulic characteristics of a stream reach are represented by a function table (FTABLE) that includes the relationships between stage, storage (volume), surface area, and discharge. From the equations shown above, it is clear that the accuracy of the FTABLE for a specific reach will be a **critical factor** in adequately representing the hydraulic radius and subsequent shear values, as a function of the stage, or depth of flow. This is especially evident for simulations of flood flows that exceed bankfull discharges; improper extension of the FTABLES can lead to erroneous shear and scour conditions during high flow events, and have major impacts on the model simulations for those events.

As part of the sediment parameterization, the model is run with the initial parameter estimates and shear stress values are output for each stream reach. For the silt and clay size particles, the critical shear stress parameters (one for scour and one for deposition) for each size are adjusted so that the model calculates scour during high flow events, deposition and settling during low flow periods, and transport with neither scour nor settling for moderate flow rates; this is shown schematically in Figure 3. In general, the values are set so that scour of clay occurs at lower shear values than for silt (i.e. clay scours before silt), and deposition of silt occurs at higher shear values than clay (i.e. silt deposits before clay).

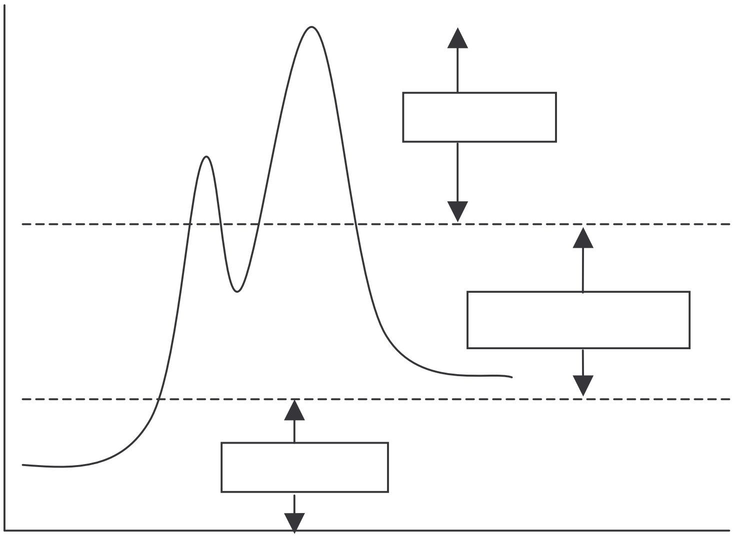


Figure 3 – Shear Stress Calculations in HSPF

Figure 4 shows an example of setting the critical shear values based on both flow and shear stress simulations for a small eastern US watershed; the top plot show the flow simulation corresponding to the shear simulations on the bottom curve. We've also included, on the right-hand scale of the shear curve, the percent exceedance values to help quantify how often scour and deposition conditions occur at different shear values.

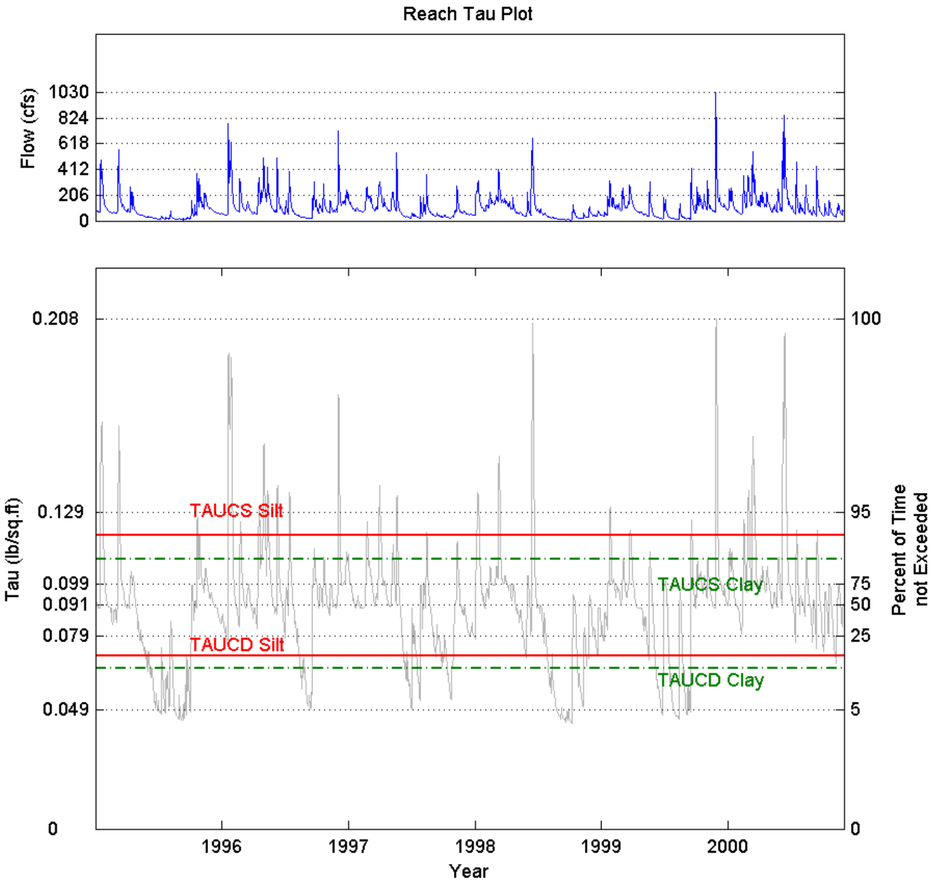


Figure 4 - Example calculations for setting critical shear values for HSPF

Step 3: Adjust Instream Scour, Deposition, and Transport parameters

Step 4: Analyze Bed Behavior and Transport Fluxes

Step 5: Analyze Overall Sediment Budgets and Stream Behavior

These 3 steps are listed together as they normally are performed while reviewing the same tabulations of model results; bed behavior and sediment budgets need to be reviewed to establish the basis for parameter adjustments on a reach-by-reach basis. Table 3 shows an example tabulation of reach-by-reach model results for a small eastern US watershed. The watershed includes 2 tributary reaches and 6 mainstem reaches, and the tabulations include sediment erosion (nonpoint) loads, point loads, upstream and total inflow loads, total outflow loads, and both cumulative and reach trapping efficiencies. For example, note that the tributaries demonstrate net scour behavior (deposition/scour column values are negative), while the mainstem is depositional throughout. This information can be compared with historical accounts or field observations to identify the 'expected' behavior for those stream segments. If this information is contrary to the model representation, i.e., the model simulates deposition when the reach is primarily being scoured, reach parameters and/or inflows need to be adjusted to correct the simulated behavior.

Table 3 – Example Tabulation of Stream Sediment Fluxes and Behavior

	Nonpoint	Point Source	Upstream In	Total Inflow	Outflow	Deposit (+) Scour (-)	Cumulative Point/NonPt	Cumulative Trapping Efficiency	Reach Trapping Efficiency
Reach Segment	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)	(%)	(%)
Mainstem 1	212.5	107.4	6,453.7	6,785.3	6,186.3	599.7	10,566.9	41.5	8.8
Mainstem 2	68.8	0.0	6,186.3	6,255.0	5,384.8	870.6	10,635.7	49.4	13.9
Tributary 1	102.4	0.0	0.0	102.2	125.0	-22.7	102.2	-22.0	-22.0
Mainstem 3	5.8	0.0	5,509.8	5,515.6	4,916.3	599.9	10,744.0	54.2	10.9
Tributary 2	281.1	0.0	0.0	280.5	352.6	-72.1	280.5	-25.5	-25.5
Mainstem 4	215.4	0.0	5,268.9	5,483.9	4,269.8	1,215.1	11,240.4	62.0	22.1
Mainstem 5	54.1	0.0	4,269.8	4,323.8	3,507.1	826.2	11,294.5	68.9	18.9
Mainstem 6	93.9	0.0	3,507.1	3,600.8	2,190.8	1,421.3	11,388.4	80.8	39.2

Table 4 shows the corresponding detailed behavior of bed depth and sediment fractions in selected reaches within the watershed (Tributary 1 and Mainstem reaches 2 and 3). The tabulations in Table 4 include, annual inflow loads, outflow loads, and deposition/scour in the reach, along with the composition of these loads and the bed behavior and composition throughout the simulation period. Field observations of bed depth changes, expected deposition rates, bed sediment composition fractions, etc. can be used to assess the validity of the model results and identify needed changes.

These results demonstrate the types of analyses performed as part of the sediment calibration effort. In this example, sand comprises a small fraction of the total sediment concentration and discharge, and thus the sand parameters are set to values to reflect this small contribution. In other watersheds, the non-cohesive (sand) fractions may be more critical and thus require greater focus and calibration effort.

The primary focus of this example calibration is the silt and clay parameters. As noted above, the shear stress values are adjusted so that scour occurs during storm periods and deposition occurs at low flows. Once the timing of scour and deposition processes is correct, the rate of scour (i.e. erodibility factor in the model) is adjusted in an attempt to match either the expected behavior within each reach, from review of the type of information shown in Tables 3 and 4, and/or the observed concentrations (discussed below in the next step). During high flow periods, the amount of scour is adjusted with an erodibility factor for each reach that controls the rate of scour whenever the actual shear stress is greater than the critical shear stress value for scour.

The need to analyze the model simulations on a reach-by-reach basis is mandated by the extreme variability in sediment processes. If upstream reaches are depositing more than expected, then inflows to downstream reaches will be less than what really occurs, requiring parameter adjustments that may not be reasonable for the downstream reaches. The opposite would occur if upstream reaches are eroding much more than expected; inflows to downstream reaches will be too large, resulting in more deposition than would be expected. If the reach parameters are set so that deposition does not occur, then the upstream eroded load will be transported and will subsequently impact other downstream reaches. Thus, an upstream to downstream analysis, on a reach-by-reach basis, is required to adequately assess model simulations.

Table 4 - Example Bed and Stream Reach Sediment Simulations

Mainstem 2								Final	Average	Arithmetic
	Init Val	1995	1996	1997	1998	1999	2000	Fraction	Fraction	Average
Bed Depth (ft)	2.00	2.10	2.10	2.10	2.20	2.20	2.30			2.20
Bed Storage (tons)										
Sand	0.79	34,684.7	34,775.7	34,795.8	34,805.4	34,828.3	34,840.5	0.70	0.73	34,788.4
Silt	0.15	7,623.7	8,780.0	9,310.2	9,867.1	10,581.5	11,573.3	0.23	0.20	9,622.6
Clay	0.07	3,112.9	3,165.8	3,181.9	3,201.7	3,222.9	3,255.5	0.07	0.07	3,190.1
Total		45,421.3	46,721.6	47,287.9	47,874.2	48,632.8	49,669.2			47,601.2
Inflow (tons)										
Sand		152.6	273.5	115.0	133.0	130.6	219.8	0.03	0.03	170.7
Silt		4,705.1	5,024.8	2,503.7	2,571.7	3,357.7	4,437.0	0.61	0.60	3,766.7
Clay		3,152.5	3,270.2	1,354.6	1,528.3	1,939.2	2,638.8	0.36	0.37	2,313.9
Total		8,010.2	8,568.5	3,973.3	4,232.9	5,427.4	7,295.6			6,251.3
Dep(+)/Scour(-) (tons)										
Sand		4.7	-0.4	22.9	12.1	25.6	14.9			13.3
Silt		1,038.4	1,135.4	530.0	556.7	714.9	991.9			827.9
Clay		39.8	44.4	16.0	19.8	21.3	32.5			29.0
Total		1,082.8	1,179.4	568.9	588.5	761.8	1,039.4			870.1
Outflow (tons)										
Sand		148.0	273.8	92.2	120.9	104.9	204.9	0.03	0.03	157.5
Silt		3,668.1	3,889.2	1,974.0	2,015.0	2,642.8	3,445.1	0.55	0.55	2,939.0
Clay		3,113.9	3,225.5	1,339.0	1,508.6	1,917.8	2,606.2	0.42	0.43	2,285.2
Total		6,929.9	7,388.5	3,405.2	3,644.4	4,665.6	6,256.2			5,381.6
Tributary 1								Final	Average	Arithmetic
	Init Val	1995	1996	1997	1998	1999	2000	Fraction	Fraction	Average
Bed Depth (ft)	2.00	2.00	2.00	2.00	2.00	2.00	2.00			2.00
Bed Storage (tons)										
Sand	0.9	28,369.1	28,440.4	28,434.4	28,415.9	28,407.7	28,417.6	0.90	0.90	28,414.2
Silt	0.05	1,569.4	1,563.8	1,561.0	1,559.1	1,554.2	1,544.3	0.05	0.05	1,558.6
Clay	0.05	1,563.0	1,549.4	1,544.4	1,538.6	1,529.9	1,513.4	0.05	0.05	1,539.8
Total		31,501.5	31,553.6	31,539.8	31,513.6	31,491.9	31,475.4			31,512.6
Inflow (tons)										
Sand		32.1	49.3	24.3	14.9	29.2	64.6	0.35	0.35	35.8
Silt		45.9	70.5	34.8	21.4	41.8	92.3	0.50	0.50	51.1
Clay		13.8	21.2	10.4	6.4	12.5	27.7	0.15	0.15	15.3
Total		91.8	141.0	69.5	42.7	83.6	184.6			102.2
Dep(+)/Scour(-) (tons)										
Sand		-0.7	-6.8	-7.3	-19.3	-8.7	9.4			-5.6
Silt		-6.6	-10.0	-2.8	-2.0	-4.8	-9.9			-6.0
Clay		-13.1	-17.8	-5.0	-5.7	-8.7	-16.5			-11.2
Total		-20.4	-34.6	-15.1	-27.0	-22.2	-17.0			-22.7
Outflow (tons)										
Sand		32.8	56.1	31.6	34.3	37.9	55.2	0.27	0.33	41.3
Silt		52.6	80.5	37.5	23.3	46.6	102.2	0.51	0.46	57.1
Clay		27.0	39.0	15.5	12.2	21.2	44.2	0.22	0.21	26.5
Total		112.4	175.6	84.6	69.7	105.7	201.6			124.9
Mainstem 3								Final	Average	Arithmetic
	Init Val	1995	1996	1997	1998	1999	2000	Fraction	Fraction	Average
Bed Depth (ft)	2.00	2.10	2.10	2.10	2.20	2.20	2.20			2.10
Bed Storage (tons)										
Sand	0.79	27,713.8	28,089.4	28,204.8	28,346.9	28,480.0	28,720.2	0.74	0.75	28,259.2
Silt	0.15	5,710.9	6,354.4	6,552.4	6,789.1	7,078.2	7,578.0	0.19	0.18	6,677.2
Clay	0.07	2,481.1	2,537.1	2,547.4	2,564.5	2,582.8	2,617.0	0.07	0.07	2,555.0
Total		35,905.8	36,981.0	37,304.6	37,700.6	38,141.1	38,915.2			37,491.4
Inflow (tons)										
Sand		182.5	332.6	125.4	156.1	144.5	263.5	0.04	0.04	200.8
Silt		3,723.3	3,973.5	2,013.7	2,039.7	2,691.8	3,552.2	0.55	0.54	2,999.0
Clay		3,141.7	3,265.6	1,355.1	1,521.2	1,939.8	2,651.9	0.41	0.42	2,312.6
Total		7,047.5	7,571.7	3,494.2	3,716.9	4,776.1	6,467.7			5,512.3
Dep(+)/Scour(-) (tons)										
Sand		164.8	300.0	116.0	142.4	133.3	240.1			182.8
Silt		480.4	627.7	198.1	236.6	289.1	499.6			388.6
Clay		40.0	49.2	10.2	17.3	18.3	34.2			28.2
Total		685.2	976.9	324.4	396.3	440.7	773.9			599.6
Outflow (tons)										
Sand		17.7	32.6	9.3	13.7	11.2	23.4	0.00	0.00	18.0
Silt		3,244.6	3,345.3	1,816.1	1,803.0	2,402.7	3,052.6	0.54	0.53	2,610.7
Clay		3,103.1	3,215.9	1,345.6	1,503.9	1,921.4	2,617.7	0.46	0.47	2,284.6
Total		6,365.4	6,593.8	3,171.1	3,320.6	4,335.3	5,693.8			4,913.3

Step 6: Compare Results with Available Data

The remaining step in the calibration procedure is to compare model simulations of concentrations and loads to available observed data. In many cases, this may be limited to event mean concentrations of total suspended solids (TSS) for selected storm events and nonstorm (baseflow) periods, or pollutographs of TSS concentrations throughout a few events. However, other types of comparisons are also possible, such as load estimates and sediment rating curves; each of these is discussed below.

Figure 5 shows an example of the conventional type of storm event comparison for TSS for the same small eastern US watershed. Clearly, such comparisons need to be made for as many storm events as there are available data. Figure 5 shows a very good simulation for both flow and TSS concentrations; most simulations will not be this good, and will show large variations from storm to storm. Even with this storm, there are inconsistencies demonstrated; the simulated flow peak is higher than the observed and precedes it, identifying a possible time lag in the peak that is not well represented in the model. In addition, the flow peak is about 25% higher than observed, whereas the TSS peak is only about 10% higher. Both of these differences may be entirely acceptable, considering the uncertainty in the observations and needed (and/or expected) accuracy of the model, but model results need to be viewed with a critical eye toward demanding consistent behavior, i.e. if flows are over-simulated then TSS should be over-simulated, and vise-versa.

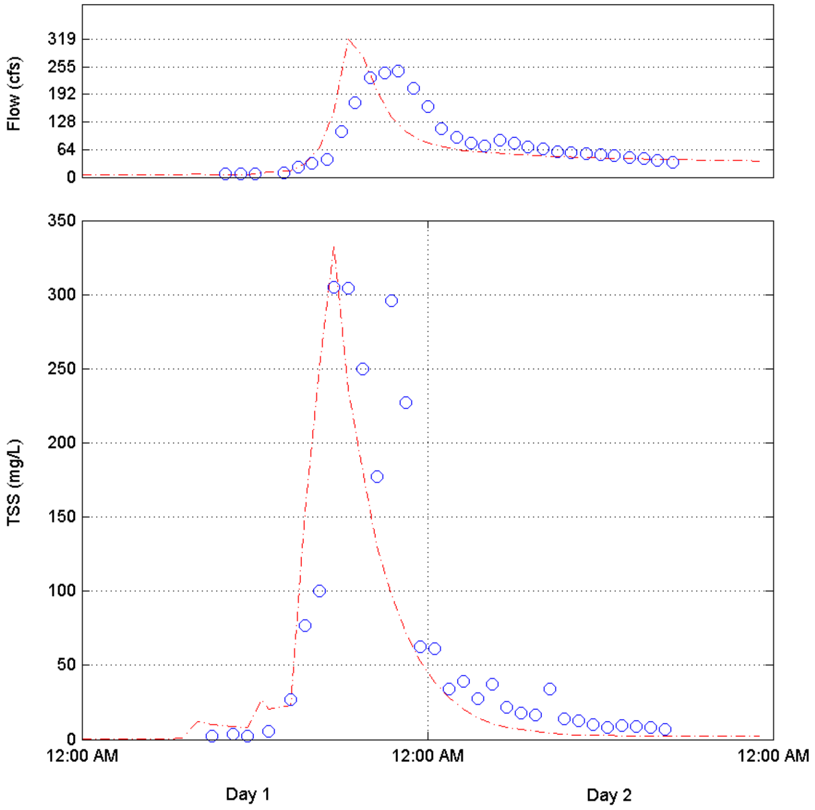


Figure 5 - Example comparison of simulated and observed storm flow and TSS concentrations

Figure 6 shows an annual plot of simulated and estimated sediment loads for the watershed outlet. In this case the 'Load Estimates' were extrapolations from available TSS data, and were **not** the results of continuous, or even daily sampling. So this comparison is really between two models: a simulation model (HSPF) and a regression model. However, even this type of comparison is useful, recognizing that differences do not necessarily detract from the validity or utility of the simulation model. This is simply one additional type of comparison that can be included in the weight-of-evidence approach to sediment calibration. The average annual values in Figure 6 indicate a very good simulation even though there are significant differences year to year. For sediment modeling these types of differences are to be expected, since, as noted earlier, sediment is one of the most difficult water quality constituents to model accurately.

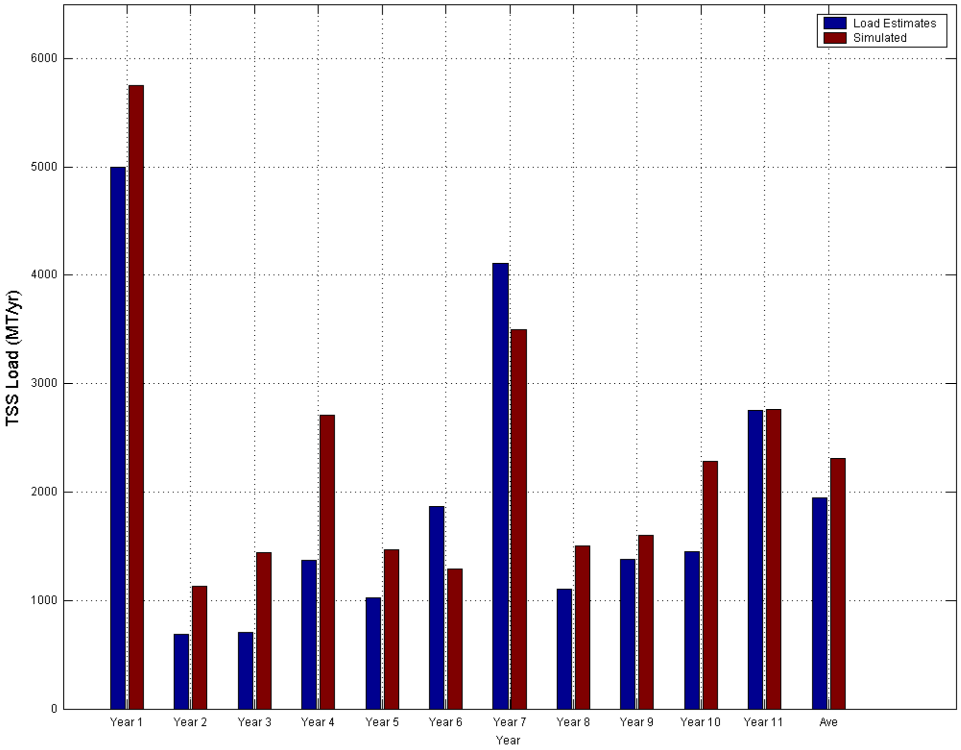


Figure 6 – Example comparison of simulated and estimated annual TSS loads

Figure 7 shows an example of comparing sediment rating curves, simulated and observed, for a single site at the watershed outlet. These curves essentially demonstrate the relationship between flow rate and sediment concentrations, and the concept in this comparison is to evaluate whether the model and the data demonstrate similar relationships. The top curve shows the flow versus load relationship, corresponding to the bottom curve of sediment concentration versus flow. Regression lines have been fitted to both the data and model results, and are shown on the curves. The log scale is used, as is typical for, and usually required for sediment rating analyses.

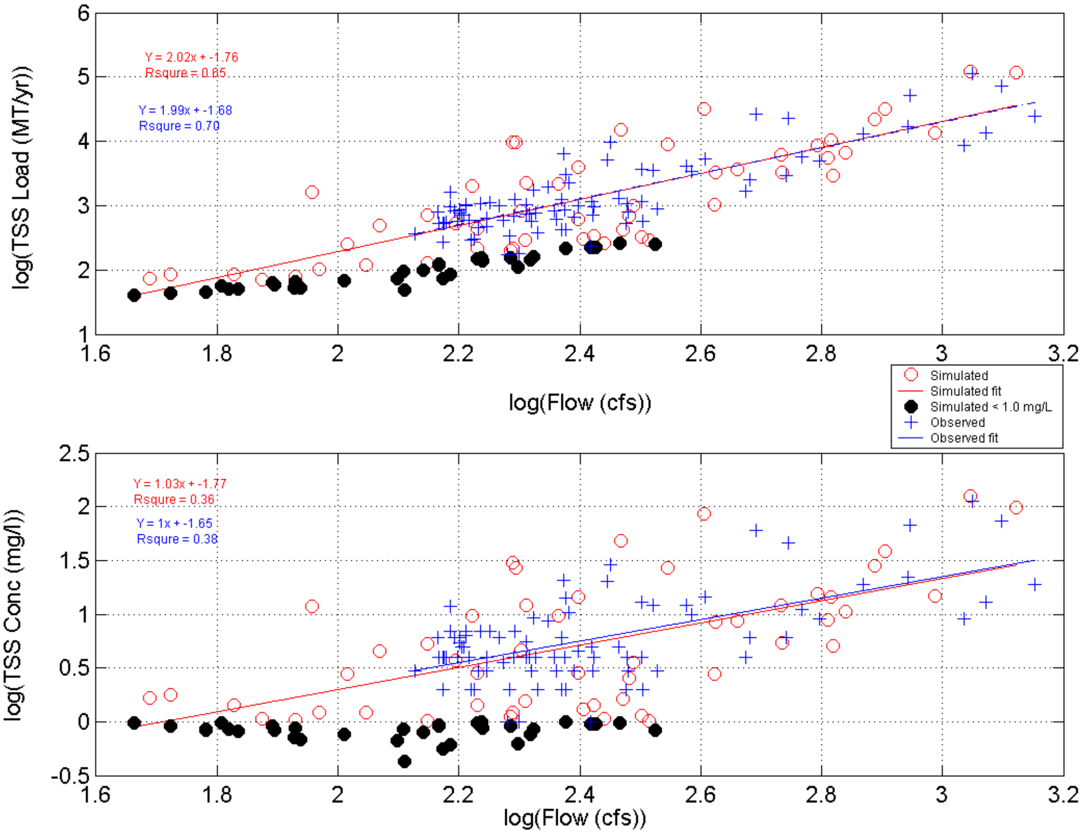


Figure 7 – Example of observed and simulated sediment rating curves

It should be noted that the regression curves are fitted to a subset of the observed and simulated values; the **solid dots were excluded from the analyses**, corresponding to TSS concentration values less than 1.0 mg/l. The rationale for this was as follows:

- The observations were performed primarily at moderate to high flow conditions, so very low concentrations would not be well represented.
- The HSPF model employs a relatively gross channel representation, with long reach lengths, that tends to eliminate localized turbulence and scour conditions that would likely contribute to under-simulating the low concentrations.
- The extremely low concentrations contribute to a small fraction of the total annual sediment load, approximately less than 3 to 5 percent of the annual load in this watershed.

The overall results in Figure 7 show a relatively good simulation of the flow-sediment relationship demonstrated in the sediment rating curves. Both the range of concentration and flow values, and the slopes of the regression lines, demonstrate consistency between the model and the observed data. If large consistent differences existed, it would justify continued calibration efforts to minimize such differences.

Step 7: Repeat Calibration Steps, as Needed, To Improve Sediment Representation

Modeling tends to be a circular, or iterative, process. For sediment calibration, Steps 3 through 6 often need to be repeated until all the components of the calibration exercise are in reasonable balance. In some cases, the process may need to reconsider the target loading rates developed in Step 1, and then re-calibrate the model rates. This might occur if the surface loadings appear to dominate unrealistically the overall watershed simulation results.

The iteration process doesn't require that every comparison be brought to the same level of agreement, but only that the entire process be repeated until the entire 'weight-of-evidence' from the simulations indicates either that the model is 'as good as it can be' or that it can not meet the specific needs of the watershed assessment. This should produce sufficient evidence that the model is either acceptable for the intended purpose, a recommendation that the model or data input improvements may be needed, or that a different model should be considered.

CLOSURE

This paper explores the 'weight of evidence' approach for sediment calibration as part of overall watershed model calibration based on recent experience with the U. S. EPA HSPF. The steps in the overall sediment calibration process are identified and discussed, along with specific issues related to model parameterization and calibration procedures. Using example applications and sample model results, we demonstrate recommended graphical and statistical procedures used to assess model performance for sediment loadings, concentrations, and budgets within a watershed modeling framework. Although the results are specific to the EPA HSPF model, the approach and procedures for sediment calibration are applicable to other watershed models that represent sediment processes and behavior at the watershed scale. Although sediment calibration remains one of the most difficult components of watershed-scale water quality assessments, it is hoped that the procedures outlined herein will provide some guidance and assistance to model users who attempt this often daunting task.

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