A Coupled Upland-Erosion and Instream Hydrodynamic-Sediment Transport Model for Evaluating Sediment Transport in Forested Watersheds

W. J. Conroy, R. H. Hotchkiss, W. J. Elliot

Abstract. *This article describes a prototype modeling system for assessing forest management-related erosion at its source and predicting sediment transport from hillslopes to stream channels and through channel networks to a watershed outlet. We demonstrate that it is possible to develop a land management tool capable of accurately assessing the primary impacts of spatiotemporally varied forest management practices on sediment yield and delivery at hillslope to watershed scales in a single simulation. The modeling system consists of four components: (1) the TOpographic ParameteriZation (TOPAZ) model for discretizing hillslope and channel elements, (2) the Water Erosion Prediction Project (WEPP) model for evaluating hillslope-scale surface erosion processes, (3) the National Center for Computational Hydrodynamics and Engineering's one-dimensional (CCHE1D) hydrodynamic-sediment transport model, and (4) an interface program to manage relational databases and data transfer between modules. The coupled models were calibrated and validated with observed flow and sediment load data from the North Fork Caspar Creek Experimental Watershed in coastal northern California. The coupled models' predictions of peak flow rate and total flow volume were not significantly different from observed values. Predicted sediment concentrations were significantly different from observed values, but within typical ranges for sediment transport equations. We recommend that the WEPP model be improved to allow access to sub-daily time scale results so that it can be better integrated with other watershed models.*

Keywords. *Erosion modeling, Hydrodynamic modeling, Watershed models, TMDLs, CCHE1D, WEPP.*

Excessive sediment is the third highest ranked category of impairment among pollutants listed by the U.S. Environmental Protection Agency (USEPA, 2005). The Clean Water Act requires development of a management plan, called Total Maximum Daily Load (TMDL), to identify, assess, and reduce anthropogenic pollutants (USEPA, 1999). A goal of sediment TMDL analyses is to track the movement of sediment from multiple sources (forced at different times), to and through a channel network, to a watershed outlet.

Accurately simulating the transport of sediment from its sources to a watershed outlet has been one of the most elusive problems in watershed hydrology (Jetten et al., 2003). For example, computer models that emphasize a deterministic simulation of soil erosion are weak when used to simulate fluvial transport through a channel system (Beven, 2001), and models that emphasize a deterministic description of fluvial transport of sediment do not use output from a physically based hillslope erosion model as input to the channel transport model (Beven, 2001).

The purposes of this article is are to: (1) describe a modeling system that couples an explicit, distributed, physically based, hillslope-scale, upland-erosion simulation model with a watershed-scale, hydrodynamic-sediment transport model; and (2) calibrate and validate the modeling system using data collected from Caspar Creek, California, a long-term experimental, paired watershed operated by the U.S. Forest Service (Henry, 1998).

Conroy (2005) critically examined several available computer models for simulating soil erosion at a hillslope scale and sediment transport through a stream channel system. Based upon his work, the best models for a coupled modeling attempt are the Water Erosion Prediction Project (WEPP) model (Flanagan et al., 1995) and the National Center for Computational Hydrodynamics and Engineering's One-Dimensional (CCHE1D) hydrodynamic-sediment transport model (Wu et al., 2004; Wu and Vieira, 2002). Each model will be briefly described; more detail may be found in Conroy (2005).

WEPP Model

The Water Erosion Prediction Project (WEPP) model (Flanagan et al., 1995) is a physically based erosion simulation model commonly used to evaluate agricultural, forest management, and wildfire effects on surface sediment

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erosion processes. The WEPP model has the ability to evaluate explicitly spatiotemporally distributed climatic and physiographic variables, making it nearly ideal for use in sediment TMDL evaluations. The WEPP model is unique among erosion models in that it explicitly evaluates water balance and surface erosion processes from a ridge top to the channel bottom of a hillslope plane. The WEPP model has two operational modes: hillslope and watershed. The hillslope mode is a field-scale simulator, and the watershed mode iteratively uses the hillslope simulator to simulate multiple hillslopes within a watershed. As will be detailed further, the watershed simulator has several weaknesses that preclude its use in our study. As such, only the hillslope simulator (hereafter denoted as WEPP Hillslope or WEPP-H) is used in this work.

Even though WEPP has many appropriate features for erosion simulations, it has two limitations that need to be improved to allow the model to be used for small watershed-scale (up to 130 km^2) analyses (USEPA, 1999). The WEPP model does not explicitly include hydrodynamic channel network flood flow routing or sediment transport algorithms. The model simulates hydrodynamics and sediment transport by using a simplified hydrologic model and a single sediment transport capacity equation (Ascough et al., 1995).

To simulate water routing from hillslopes, to and through a channel network, WEPP applies modifications to the Rational (McCuen, 1998) and Soil Conservation Service Curve Number (USDA-SCS, 1991) methods. These methods are not rigorous, since they are only capable of determining the peak runoff and/or volume (USACE, 1994), and they ignore the physical processes governing open channel flow. The accuracy of runoff simulations in watersheds approaching the upper limit of “small” (130 km^2) is severely limited by not including a hydrodynamic procedure.

The WEPP model uses a modified form of Yalin’s bedload equation (Yalin, 1963) to compute sediment transport capacity in rills, interrill areas, and channels. Yalin’s equation has been successfully applied to overland flow sediment transport in interrill areas by several authors (Alonso et al., 1981; Ferro, 1998; Finkner et al., 1989; Wicks and Bathurst, 1996) but has been demonstrated as inadequate for bedload transport in rivers (Bravo-Espinosa et al., 2003). Therefore, to improve the accuracy of watershed simulations with the WEPP model, appropriate methods for simulating open channel flow and sediment transport are needed.

The full St. Venant dynamic wave equations are considered to be the most accurate and comprehensive solution to 1-D unsteady flow problems in open channels (USACE, 1994) and are generally the standard to which other flow routing methods are compared. Several publicly and commercially available models have implemented the full dynamic wave equations for routing water through a network of channels. For example, the U.S. Geological Survey has three separate models: the Branch-Network Dynamic Flow model (BRANCH; Schaffranek et al., 1981), the Full Equations model (FEQ; Franz and Melching, 1997), and FourPT (DeLong et al., 1997). In addition, the Danish Hydrological Institute has developed the MIKE-11 hydrodynamic model as a component for its SHE modeling system (Yan and Zhang, 2001), and the National Center for Computational Hydroscience and Engineering, in conjunction with the USDA Agricultural Research Service, has developed the CCHE1D model (Vieira and Wu, 2002). The CCHE1D model was selected for this work because it combines hydrodynamic routing with sediment transport.

CCHE1D MODEL

The Center for Computational Hydrodynamics and Engineering One-Dimensional (CCHE1D) model is unique among hydrodynamic-sediment transport models in that it explicitly evaluates the full equations of motion (i.e., St. Venant equations) and the sediment continuity equation (i.e., Exner equation) for all channel segments in large (more than 130 km^2) watershed networks (USEPA, 1999). The model was designed to simulate unsteady flows and sedimentation processes in watershed-scale channel networks including bed aggradation and degradation, bed material composition (hydraulic sorting and armoring), bank erosion, and the resulting channel morphologic changes.

By design, CCHE1D does not include an upland erosion algorithm to simulate sediment delivered to channels. Instead, the model must be integrated with an existing watershed process model (rainfall-runoff and field erosion) to receive sediment input as part of the boundary conditions (Wu and Vieira, 2002). For example, the CCHE1D hydrodynamic-sediment transport model has been coupled with AGNPS (Young et al., 1989) and SWAT (Neitsch et al., 2001) to produce an integrated watershed-scale erosion model (Wang et al., 2002).

Although CCHE1D is a physically based hydrodynamic-sediment transport model, both AGNPS and SWAT are grid-based, empirical erosion models that are based on modifications to the USLE (McCuen, 1998). Empirical models can be calibrated to produce reasonably accurate simulation results. However, because physical processes are typically ignored, the validity of results is highly questionable when the models are applied to conditions outside of those for which they were developed. It is therefore more appropriate to simulate both upland erosion and instream hydrodynamics with physically based models. This procedure is described next.

COMPUTER SIMULATION

STUDY AREA

The Caspar Creek Experimental Watershed (CCEW) is located in the Jackson Demonstration State Forest in northwestern coastal California. The CCEW consists of the 424 ha South Fork and 473 ha North Fork sub-watersheds (Henry, 1998). For this research, only the managed North Fork Caspar Creek Watershed (NFCCW) (harvested between 1989 and 1991) was used for both model calibration and validation (fig. 1). The primary land-use/land-cover in the NFCCW is coniferous forest, consisting mainly of dense stands of second-growth Douglas fir (*Pseudotsuga menziesii*) and coast redwood (*Sequoia sempervirens*) (Henry, 1998). The elevation of the watershed ranges from 37 to 320 m above mean sea level. Hillslope gradients are generally less than 70%, but often exceed 70% adjacent to deeply incised streams (Henry, 1998).

NFCCW experiences a Mediterranean climate (Henry, 1998). Mean annual precipitation is 1,190 mm and has ranged from 305 to 2,007 mm over the 1962-1997 period of record (Henry, 1998). Summer thunderstorms and winter snowfall

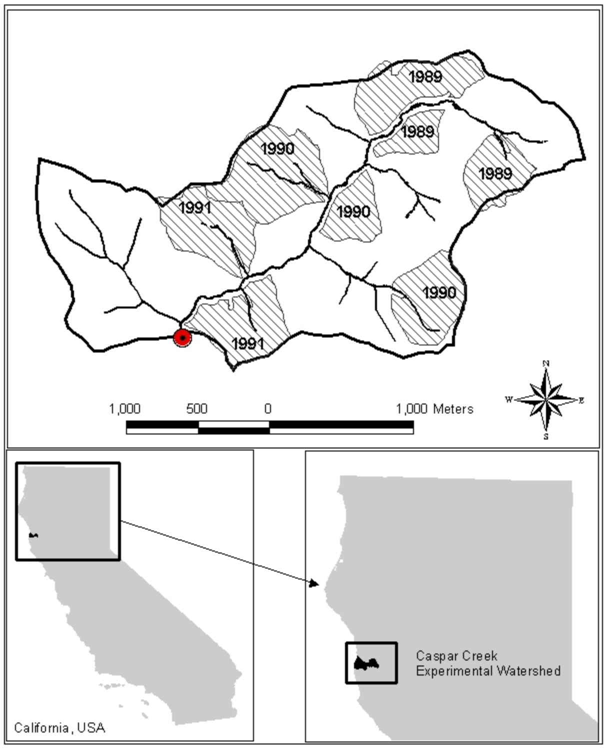

Figure 1. North Fork Caspar Creek Watershed in the Caspar Creek Experimental Watershed, northwestern coastal California. Watershed outlet is coincident with stream and suspended sediment gauging stations, indicated by crossed circle. Harvested areas shown by year of harvest.

are both very rare for this region. Summers are relatively dry, with cool coastal fog that contributes a small portion of the annual precipitation and reduces evapotranspiration losses. Temperatures are mild with muted annual extremes and narrow diurnal fluctuations due to the moderating effect of the Pacific Ocean (Henry, 1998).

NFCCW streamflows follow the precipitation pattern, with winter maximum flows three orders of magnitude larger than summer minimum flows. Highest streamflows generally occur in November through February, the result of low-intensity, long-duration rainfall events. Bankfull discharge rate is approximately 3.0 m^3/s (Lisle, 1995). Soils consist of well-drained clay-loams 1 to 2 m deep that have high saturated hydraulic conductivities (50 to 100 mm/h). The dominant mechanism for generating stormflow is lateral subsurface flow (Keppeler and Brown, 1998). Saturated overland flow occurs only for short durations (Henry, 1998) from areas adjacent to stream channels and areas that have low saturated hydraulic conductivity (e.g., roads and landings).

Channel sediment transport moves sediments smaller than large gravels, including a significant sand and silt component (Lisle, 1995). As with streamflow, sediment transport exhibits strong seasonality, with minimal or no movement during low-flow periods and very high sediment loads during winter rainstorms. The observed bed material composition at the outlet of the NFCCW is largely gravel and cobble (table 1). The median particle diameter is 24 mm, with less than 16% sands or finer (Lisle, 1995). All of the bedload in classes 6 through 12 and approximately 40% of the suspended load are trapped in weir ponds upstream of the suspended sediment sampling station (Lewis et al., 2001).

Table 1. Fraction of bed material, by size class (with upper and lower limits and representative diameter), for North Fork Caspar Creek (Lisle, 1995).

Sediment Size Class	Representative Diameter of Class (mm)	Lower Limit of Class (mm)	Upper Limit of Class (mm)	Fraction of Bed Material in Class	Specific Gravity
1	0.002	0.001	0.004	0.010	2.60
2	0.010	0.004	0.016	0.010	2.65
3	0.030	0.016	0.062	0.020	1.80
4	0.200	0.062	0.250	0.040	2.65
5	0.500	0.250	2	0.075	1.60
6	2.83	2	4	0.077	2.65
7	5.66	4	8	0.125	2.65
8	11.3	8	16	0.163	2.65
9	22.6	16	32	0.200	2.65
10	45.3	32	64	0.175	2.65
11	90.5	64	128	0.095	2.65
12	181	128	256	0.010	2.65

Pumped sediment samples using an ISCO automatic sampler were adjusted by depth-integrated hand samples to produce a composite suspended sediment concentration for the entire channel cross-section (Lewis et al., 2001). The observed suspended sediment concentration values in Caspar Creek are from regression equations that relate discharge to point samples of suspended sediment.

Modeling Components

Overview

The modeling system described in this article uses an aggregated, distributed parameter approach to model hillslope-scale runoff and erosion and watershed-scale flow and sediment transport. As shown in figure 2, the TOpographic PArameteriZation (TOPAZ; Garbrecht and Martz, 1995) digital landscape evaluation tool runs internally from both WEPP and CCHE1D modeling systems and was used to delineate channel networks and discretize sub-watershed boundaries from 10 m digital elevation models (DEMs). The WEPP-Hillslope (WEPP-H) model was used to determine the runoff volume and sediment load for each hillslope element separately. Data from the CCHE1D and WEPP-H output files were processed with the interface program written for this effort. The data files generated from the interface program were used to run the CCHE1D simulations. Finally, output data from WEPP-H and CCHE1D were post-processed for comparison with observed data.

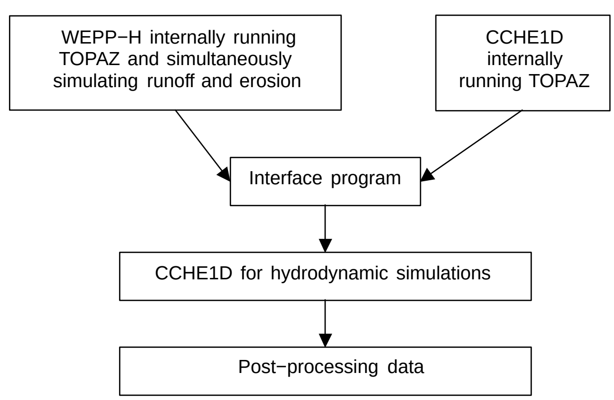

Figure 2. Flowchart for modeling system.

TOPAZ Landscape Evaluation Tool

TOPAZ requires the user to define the minimum allowable area above the head of a first-order channel (Garbrecht and Martz, 1995). This area, called the critical source area (CSA), is the basis for defining limits on the length and width of hillslope elements. In practice, the CSA is set equal to the size of management units (or mapped sub-watersheds), or the CSA is changed until the derived channel network visually matches the observed channel network (Cochrane and Flanagan, 1999). For this research, the minimum source area was fixed at 10 ha and the minimum channel length was fixed at 100 m to limit the size of hillslopes simulated by WEPP-H and to match the derived channel network and sub-watershed boundaries with those mapped. Other TOPAZ-derived data are described in the appropriate model section below.

WEPP Hillslope Upland Erosion Model

The WEPP model (version 2004.610, released June 2004) requires four input data files: climate, landscape geometry, soil, and plant management. Required climate data were extracted from the CCEW databases, including daily values for temperature (max/min), solar radiation, and wind speed (table 2). Instantaneous values for precipitation from tipping-bucket rain gauges were aggregated into hourly totals for each rainstorm analyzed. Landscape geometry data were automatically generated by TOPAZ from a 10 m DEM. Soil data were extracted from the CCEW databases, including, depth, organic matter content (table 3), and particle size gradation (table 1). The forest management files from the WEPP-H databases were used to describe plant/management conditions (tables 4 and 5). These files were modified to adjust plant spacing, tree height, and leaf area index based on typical growth and yield conditions for the region (Lindquist and Palley, 1967; McArdle et al., 1961) and recorded post-harvest conditions (Henry, 1998). The fixed variables (table 4) are set to maximum allowable values and are adjusted internally by the WEPP-H model. The variable parameters (table 5) were adjusted to simulate changes in ground cover and tree growth between years after harvesting.

Interface Program

To facilitate data transfer between WEPP-H and CCHE1D, an interface module was written in FORTRAN for this research project. The purpose of the module is to ensure that the data necessary to run CCHE1D are provided with the correct units and formatting. The interface program: (1) creates a relational database to uniquely organize watershed structure; (2) extracts rainfall, runoff, baseflow, and sediment load data from WEPP-H input and output files; (3) converts the data into consistent units (e.g., depth to volume, seconds to hours); (4) generates time-series hydrographs for each channel segment in the watershed network; (5) generates, where necessary, cross-sectional geometry at channel nodes; and (6) creates properly formatted text files necessary to run the CCHE1D simulations.

Table 2. Observed monthly average climate parameters for Caspar Creek, California (1989-1997) used in WEPP-Hillslope simulations.

	Temperature (°C)			
Month	Maximum	Minimum	Solar Radiation (Langleys)	Rainfall (mm)
Jan.	8.9	7.3	125	236.0
Feb.	9.3	8.3	202	144.7
Mar.	10.4	9.2	292	200.4
Apr.	12.0	9.1	393	89.6
May	14.1	10.0	507	77.2
June	15.9	11.1	591	22.2
July	17.4	12.2	621	0.8
Aug.	16.7	12.4	535	4.6
Sept.	14.9	11.9	456	11.2
Oct.	12.4	10.3	323	62.0
Nov.	9.7	8.2	201	97.8
Dec.	8.5	7.3	123	224.6

CCHE1D Hydrodynamic-Sediment Transport Model

The CCHE1D model requires physiographic, runoff, and sediment data to operate. Data acquisition and development are described separately below.

Physiographic data. Physiographic data include channel network geometry, channel cross-sections at each source and junction node, and channel roughness (Manning's n) for each reach. Channel network geometry data were automatically generated with TOPAZ, requiring only a relational table to maintain the spatial properties between WEPP-H and

Table 3. User-defined input soil property parameters used for WEPP-hillslope simulations.

Soil Property	Value
Depth (mm)	1525
Texture class	Clay loam
Sand content (%)	30.0
Clay content (%)	25.0
Organic matter content (%)	3.0
Rock content (%)	2.0
Initial saturation (m/m)	0.50
Effective hydraulic conductivity (mm/h)[a]	75.0[a]
Baseline interrill erodibility parameter (kg*s/m^4)	300,000
Baseline rill erodibility parameter (s/m)	0.0003
Baseline critical shear parameter (n/m^2)	4.0

[a] Calibration variable.

Table 4. Fixed, user-defined input plant growth/management parameters used for WEPP hillslope simulations.

	Management File Parameters	
Plan	20-Year-Old Forest (from WEPP-H database)	Clearcut Forest (maximum values)
Operations	None	Harvest all crops
Crop type	Perennial	Perennial
Growth pattern	Continuous	Continuous
Stem diameter (m)	1.0	0.3
Canopy height (m)	50.0	10.0
Spacing (m)	2.0	0.3
Canopy cover coefficient	20	14
Canopy height coefficient	23	3

Table 5. Variable, user-defined input plant growth/management parameters: ground cover, canopy cover, leaf area index, and biomass conversion ratio values used for WEPP Hillslope simulations.

Simulation Period	Ground Cover (%)	Canopy Cover (%)	Leaf Area Index	Biomass Conversion Ratio
Pre-harvest	100	100	30	300
Year of harvest	75	75	7.5	20
1 year post-harvest	75	75	7.5	20
2 years post-harvest	85	85	15	50
3 years post-harvest	95	95	25	150
4 (and above) years post-harvest	100	100	30	300

CCHE1D. Since it is rare to have cross-section data for every reach in a watershed, even for extensively studied areas, it was necessary to develop a method for generating these data automatically.

The method developed for this research, has five basic steps: (1) determine the location of channel network computational nodes where cross-sections are needed using TOPAZ, (2) compute the drainage area above each cross-section location with TOPAZ, (3) calculate hydraulic geometry parameters for each cross-section using regional hydraulic geometry relations found in Conroy (2005), (4) calculate the spatial coordinates of the cross-section features using TOPAZ elevation data and the calculated hydraulic geometry parameters, and (5) prepare the data in a format usable by CCHE1D.

Runoff data. WEPP-H produces outflow hydrographs that are rectangular in shape with a duration of 24 h or less (rectangle ABCD in fig. 3). Since a rectangular hydrograph is not realistic, and since it is necessary to have sub-daily time step information (e.g., minutes to hours) to run the CCHE1D model properly, adjusted hydrographs with an hourly time step were generated for this project. The purpose for approximating the hydrographs was to simulate actual conditions better than the current WEPP-H output. The generated hydrographs should still be considered approximate because it was not the purpose of this study to change the hydrograph methodology for WEPP-H.

Three parameters are necessary to define the shape of a hydrograph: the duration of the rising limb, the peak flow rate, and the duration of the falling limb (fig. 3, points X, Y, and Z, respectively). The WEPP-H runoff volumes were held constant and hydrograph shape parameters were adjusted based on several, observed, single-storm, single-peak hydrographs from the North Fork Caspar Creek historic record.

The rising limb was assumed to be linear based on initial and flow rates and rise time. Since all WEPP-H output events start at midnight on a given day, it was assumed that runoff actually begins at a time equal to the start time of precipitation (for a given day) plus the time of concentration given by WEPP-H. It was assumed that the difference between the start time of precipitation and the time of maximum precipitation intensity represents the time to peak.

Twenty-three single-storm, single-peak hydrographs from the North Fork Caspar Creek historic record were analyzed to obtain realistic hydrograph recession decay rates. As is customary, discharge is a function of the discharge at the previous time step multiplied by a decay rate factor (always less than unity):

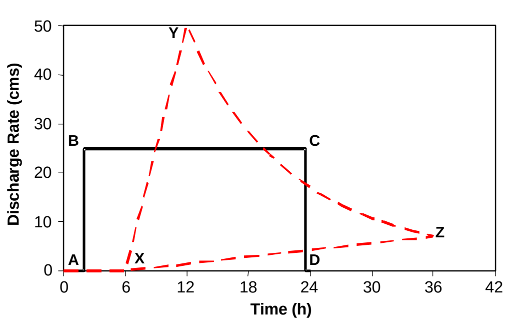

Figure 3. Adjusted hydrograph (dashed-line area XYZ) with volume equal that of rectangular hydrograph (solid-line area ABCD).

$$Q_{t+1} = Q_t * K_f \quad (1)$$

$$K_f = 0.97 * (Q_{t-1})^{-0.012} \quad (2)$$

where Q is discharge (m^3/s), t is the time step (h), and K_f is the decay factor (no units). These equations were used to generate both the recession limb discharge rates and baseflow recession discharge rates.

The end time of direct runoff was computed as the average of values computed from the same 23 observed hydrographs. The point on the recession limb where direct runoff ends was assumed to be the inflection point, i.e., the point where the recession slope changes from greater than one to less than one (McCuen, 1998). Only 15 of the 23 hydrographs had identifiable inflection points on the recession limbs. Of these 15 hydrographs, the average time to end of direct runoff (calculated from the time to peak) was 22 h. This value was added to the time of event maximum precipitation intensity to establish a duration for each runoff event. With a given runoff volume and runoff duration, the binary search method of Burden and Faires (2001) was used to find the peak flow rate such that the volume of the adjusted hydrograph equaled the observed runoff volume (fig. 3).

CCHE1D requires a continuous hydrograph to simulate hydrographs that are closely spaced in time (i.e., where direct runoff from a new event occurs before baseflow from a preceding event has ceased). It was assumed that daily runoff events were continuous as long as there were less than four days separating daily rainfall events. This criterion is based on the observed time from peak discharge to return to baseflow conditions of historic hydrographs in the watershed. For more closely spaced runoff events, it was assumed that portions of hydrographs that overlap in time are additive.

Sediment data. For the sediment transport simulations, it was necessary to define 12 sediment size classes (table 1). The five finest classes have the same limits, representative diameters, and specific gravities as those used by the WEPP-H model. The five coarsest classes were defined such that all classes of observed bed material in North Fork Caspar Creek (Lisle, 1995) would be included. Specific gravity for sediment in these classes was set at 2.65, the average value for sand particles (Brady, 1990).

Sediment transport options used in all CCHE1D simulations are summarized in table 6. Unless otherwise indicated, default settings were used. The computational time step was reduced from 15 to 5 min to ensure numerical stability throughout the simulation. The bank stability analysis option was disabled because the research was designed only to evaluate the transport of sediment from upland areas via surface erosion to and through a channel network. The erodible bed option was enabled to allow resuspension of bed material that may deposit during a hydrograph recession. However, the maximum erodible depth was set to 0.00 m so that cross-sectional geometry could be held constant throughout the simulation. This was necessary because time-series cross-section data were not available for the time period assessed, so there was no method to calibrate modeled scour depths.

Statistical Analyses

Predicted and observed values were compared for three variables: daily peak runoff rate, daily total runoff volume,

Table 6. Sediment transport parameters and options used for North Fork Caspar Creek, California, CCHE1D simulations.

Sediment Transport Option	Value	Default Value
Computational time step (min)	5	15
Hydrograph type	Time-series (1 h time step)	None
Downstream boundary condition	Open (computed at each time-step)	User specified stage time series
Baseflow discharges	User specified	User specified
Flow model	Dynamic wave	Diffusion wave
Small depth algorithm	Enabled	Enabled
Sediment transport equation	(Wu et al., 2000)	(Wu et al., 2000)
Bank stability analysis	Disabled	Enabled
Computation of bedload adaptation length	Function of alternate bar length	Function of alternate bar length
Computation of suspended load adaptation length	0.5	User specified (but default value is 0.5)
Computation of washload adaptation length	Infinite	Infinite
Computation of washload size classes	Function of rouse parameter	Function of rouse parameter
Computation of mixing layer thickness	Related to grain size	Related to grain size
Minimum mixing layer thickness (m)	0.05	0.05
Computation of bed porosity	(Komura and Simons, 1967)	(Komura and Simons, 1967)
Initial bed porosity	0.30	None (user specified)
Erodible bed	Enabled	None (user specified)
Maximum erodible depth of bed (m)	0.00	None (user specified)

and daily peak total sediment concentration. In NFCCW, the suspended fraction of the total load only includes particles less than 2 mm because 40% of the suspended load (coarser than 2 mm) is trapped upstream from the sampler. Therefore, to compare observed suspended sediment concentration values with predicted total sediment concentration values, only sediment classes 1 through 5 were included in the computations, and the predicted sediment concentration in each of these classes was reduced by a constant factor of 40% to account for the load trapped by the upstream weir.

A one-way ANOVA (Dean and Voss, 1999) was used to test for significant differences between modeled and observed results using SAS Version 9.00 statistical analysis software (SAS, 2002). The Nash-Sutcliffe coefficient (NS) of model efficiency was used as a statistical criterion for evaluating hydrologic goodness of fit between measured and predicted values for each variable tested (Nash and Sutcliffe, 1970). This statistic is recommended by the American Society of Civil Engineers Watershed Management Committee for evaluating the performance of models that simulate continuous runoff hydrographs (ASCE, 1993). As such, two hydrograph-related output parameters were evaluated: daily streamflow volume and peak discharge rate. The Nash-Sutcliffe coefficient is calculated with equation 3:

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{n}(Qo_i - Qm_i)^2}{\sum_{i=1}^{n}(Qo_i - \overline{Qo})^2} \quad (3)$$

where Qo_i are the observed values (e.g., volume or flow rate), Qm_i are model predicted values, and n is the number of data pairs. An NS value of one indicates a perfect fit between measured and predicted values and would plot as a 1:1 line. A value of zero suggests that the fit is as good as using the average value of all the measured data for each event, indicating a poor model fit. Negative NS values (having no lower limit), generally considered meaningless (ASCE, 1993), indicate poor predictive value of the model, with more negative values indicating a poorer model fit.

Results and Discussion

The TOPAZ-generated watershed structure contained 53 unique hillslopes and 21 channel segments for the NFCCW. The erosion simulation was conducted using the WEPP-H Windows interface for a nine-year simulation period from 1 January 1989 to 15 January 1997. The first three years were used as the calibration period, with the remaining six years used for validation. The calibration phase included only the three years during which the watershed was undergoing timber harvesting. The validation phase included the six-year period after harvesting was completed. The validation phase was extended beyond the length of the calibration phase for two reasons: (1) to include the time for re-growth back to 100% ground cover (assumed to be four years), and (2) to include two wet winters (1996 and 1997) with higher-than-average runoff events.

To calibrate the predicted upland water balance and sediment yield rates with observed data, only the soil surface effective saturated hydraulic conductivity variable was changed. The initial 15 mm/h was systematically incremented by 15 mm/h until satisfactory calibration was achieved with the final value of 75 mm/h. To calibrate the streamflow and instream sediment transport rates, only the channel roughness parameter (Manning's n) value was changed. The initial value of 0.075 for all streams was finalized at 0.125 for first-order streams and 0.075 for second-order streams. Calibration was deemed successful when there was no significant difference between observed and predicted values (using a one-way ANOVA), and the maximum Nash-Sutcliffe model efficiency coefficient was achieved. The validation run was completed using calibrated input and run-time parameters/options for the six-year period following the calibration period.

In the calibration period, there were 112 days where runoff and sediment loads were predicted by the WEPP-H model. All 112 days were used to compare peak daily runoff rate and total daily runoff volume with observed values. Of the 112 days, only 45 were used to compare total sediment peak concentration to observed values due to gaps in observed data (Henry, 1998). In the validation phase, there were 399 days where runoff and sediment loads were predicted by the WEPP-H model. All 399 days were used to compare peak

Table 7. Summary statistics of observed and predicted daily peak runoff rates in North Fork Caspar Creek, California.

	Calibration Run		Validation Run	
	Observed	Predicted	Observed	Predicted
Number of values	112		399	
Average (m^3/s)	0.40	0.47	0.65	0.72
Standard deviation	0.55	0.68	0.95	1.12
Maximum (m^3/s)	4.15	4.45	6.66	6.86
Minimum (m^3/s)	0.02	0.04	0.01	0.04
Sum	44.9	52.1	259	289
F-statistic	0.08		0.23	
p-value	0.78		0.63	
NS coefficient	0.42		0.70	
Significant difference from observed	No		No	

daily runoff rate and total daily runoff volume with observed values, but only 181 were used to compare total sediment peak concentration to observed values.

Peak Daily Runoff Rates

Both calibration and validation phases produced daily peak runoff rates that were not significantly different from observed rates (table 7). Predicted values had comparable ranges to those observed, and are thus reflected in very reasonable Nash-Sutcliffe coefficients (table 7) and consistent scatter about the 1:1 agreement line (fig. 4).

The approximate method used to produce hydrographs yields results that are comparable to those observed (fig. 5). However, there are two noticeable limitations to using the approximate method developed for this project. First, days with multiple peaks (as on 31 December 1996 in fig. 5) cannot be simulated without input hydrographs that also demonstrate multiple peaks. Second, this method predicts the timing of peaks and the beginning of runoff sooner than observed (fig. 5). This is because, when developing hydrographs from only total runoff volume, it was assumed that the peak of the daily hydrograph occurred at the same time as the peak precipitation intensity. The lag time between rainfall and runoff was not included in the hydrograph formulation because it was unavailable for each individual hillslope. Lag time is calculated by the WEPP Hillslope model but is not included in the output files. Including these data would greatly simplify the process of hydrograph generation. Modifying the WEPP source code was beyond the scope of this project.

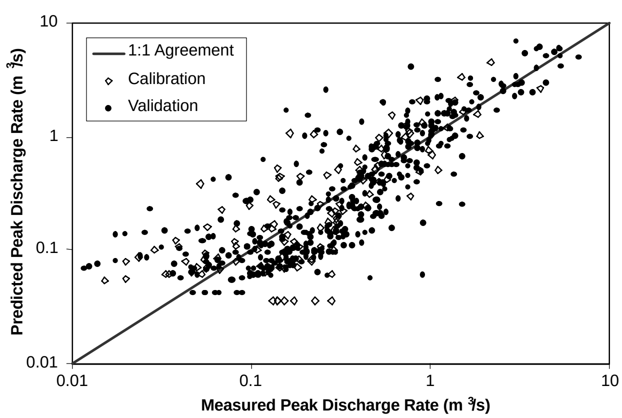

Figure 4. Measured vs. predicted daily peak discharge rate for calibration and validation model runs on North Fork Caspar Creek, California.

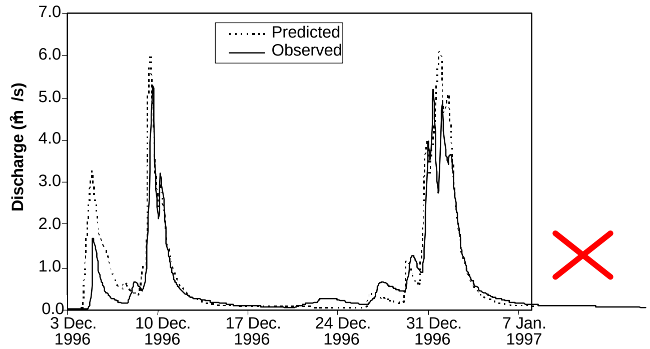

Figure 5. Observed and predicted hydrographs for a selected series of calibrated runoff events in December 1996 at North Fork Caspar Creek, California.

Total Daily Runoff Volume

As with peak runoff rates, both calibration and validation phases produced daily runoff volumes that were not significantly different from observed rates (table 8). Predicted values had comparable ranges to those observed, and are thus reflected in very reasonable Nash-Sutcliffe coefficients (table 8) and consistent scatter about the 1:1 agreement line (fig. 6). For daily runoff volume, these results are not surprising. The WEPP Hillslope model produced reasonable estimates of daily runoff volume, and the hydrodynamic model results of routed runoff through the stream channel network produced results that are comparable to observed values.

Peak Daily Total Sediment Concentration

The calibration run produced maximum daily total sediment concentrations that were not significantly different from observed rates (table 9). The validation run, however, produced results that were significantly different from observed values (table 9). Predicted values for both calibration and validation runs had comparable ranges to those observed but have significant scatter about the 1:1 agreement line (fig. 7) and led to lower Nash-Sutcliffe coefficients (table 9).

Although the model efficiency is relatively low, these results are typical of sediment transport models (Jetten et al., 2003; Yang, 1996), even when those models use observed instead of predicted sediment loads for upstream boundary

Table 8. Summary statistics of observed and predicted total daily runoff volume in North Fork Caspar Creek, California.

	Calibration Run		Validation Run	
	Observed	Predicted	Observed	Predicted
Number of values	112		399	
Average (m^3/day)	24,840	26,948	38,620	41,446
Standard deviation	34,300	35,759	50,456	60,221
Maximum (m^3/day)	286,226	217,089	356,911	389,046
Minimum (m^3/day)	722	2,714	946	2,565
Sum	2,782,059	3,018,204	15,409,412	16,536,834
F-statistic	0.26		0.19	
p-value	0.61		0.66	
NS coefficient	0.44		0.63	
Significant difference from observed	No		No	

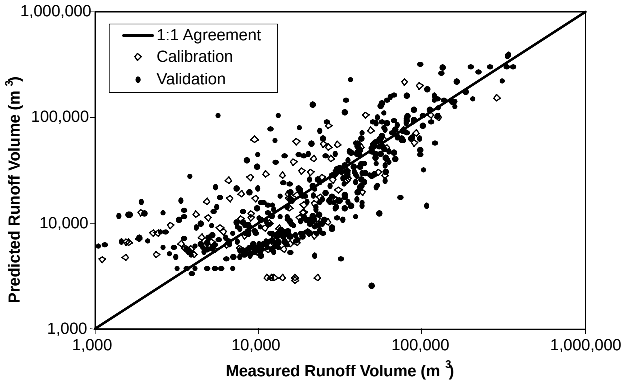

Figure 6. Measured vs. predicted total daily runoff volume for calibration and validation model runs on North Fork Caspar Creek, California.

Table 9. Summary statistics of observed and predicted daily maximum total sediment concentration in North Fork Caspar Creek, California.

	Calibration Run		Validation Run	
	Observed	Predicted	Observed	Predicted
Number of values	45		181	
Average (mg/L)	37	37	153	129
Standard deviation	63	31	342	319
Maximum (mg/L)	372	117	2,720	1,987
Minimum (mg/L)	2.11	1.02	1.74	2.22
Sum	1,682	1,687	27,754	23,371
F-statistic	0.42		8.3	
p-value	0.52		0.0042	
NS coefficient	0.29		0.09	
Significant difference from observed	No		Yes	

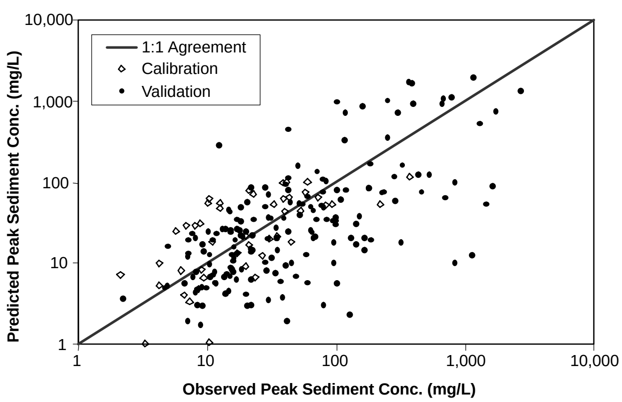

Figure 7. Measured vs. predicted peak sediment concentration for calibration and validation model runs on North Fork Caspar Creek, California.

conditions. Most of the predicted peak suspended sediment concentrations are within an order of magnitude of the observed values. Of the 226 values compared, 103 (46%) were within a factor of two, 176 (78%) were within a factor of four, and only 14 (6%) were greater than a factor of ten (i.e., an order of magnitude). The CCHE1D model developers (Wu and Vieira, 2002) reported similar results for the accuracy of the Wu et al. (2000) sediment transport capacity equation (also used for the current simulations) when they tested their model using sediment transport data collected by Toffaleti (1968) on the Rio Grande, Middle Loup, Niobrara, and Mississippi Rivers. Toffaleti's data covered a wider range of flow rates than were simulated here (up to 21,600 m^3/s) but had similar sediment sizes (0.062 to 1.0 mm) to those in this study (table 4).

Conclusion

The modeling framework presented here provides a significant advancement in the development of physically based, spatially distributed erosion simulation models. The integration of a small-scale erosion model with a large-scale hydrodynamic-sediment transport model can be used for numerous watershed-scale nonpoint-source sediment erosion analyses. By retaining the small-scale upland erosion model, individual, site-specific, erosion prevention best management practices can be evaluated. By using a large-scale hydrodynamic-sediment transport model, systems of best management practices that are spatially, temporally, and physically disparate can be evaluated. Although not explored in this research, this modeling system may be suitable for evaluating the cumulative watershed effects (e.g., aggradation or degradation of any reach in the channel network) due to forest management practices.

Linking an upland erosion model like WEPP with a hydrodynamic-sediment transport model like CCHE1D is certainly viable. WEPP evaluates erosion processes at small scales (e.g., hillslope and sub-watershed), and CCHE1D evaluates hydrodynamic-sediment transport processes at large scales (e.g., watershed network). By linking these two models, we can take advantage of beneficial features of both models, such that large watersheds can be evaluated at a very fine resolution. The resultant product would be a comprehensive, integrated watershed-scale, erosion simulation, and hydrodynamic-sediment transport model. This improvement is important for increasing the overall accuracy of surface runoff/erosion estimates associated with implementation of effective erosion control measures within ungauged watersheds. With the new procedures in place and validated, the hybrid CCHE1D-WEPP model would be available for use in modeling effectiveness of varying BMP systems used for sediment TMDL implementation, such that multiple, spatially varied management activities can be modeled and evaluated.

One notable limitation of WEPP-H is that the model stores only daily summary information, even though it generates sub-daily hillslope runoff and sediment delivery information. This limitation precludes the model from being fully integrated with other watershed models that require sub-daily time series data. This is why an empirical hydrograph method was used to link the two physically based models. Access to sub-daily time series runoff and sediment load data would certainly improve the ability to compare predicted to observed values of discharge and sediment load. Future versions of WEPP should allow access to these data, either directly while the simulations are running or indirectly through a series of output files that can be post-processed.

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References

ASCE. 1993. Criteria for evaluation of watershed models (ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models of the Watershed Management Committee Irrigation and Drainage Division). *J. Irrigation and Drainage Eng.* 119(3): 429-442.

Alonso, C. V., W. H. Neibling, and G. R. Foster. 1981. Estimating sediment transport capacity in watershed modeling. *Trans. ASAE* 24(5): 1211-1220, 1226.

Ascough, J. C., C. Baffaut, M. A. Nearing, and D. C. Flanagan. 1995. Chapter 13: Watershed model channel hydrology and erosion processes. In *Technical Documentation: USDA-Water Erosion Prediction Project (WEPP).* D. C. Flanagan and M. A. Nearing, eds. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.

Beven, K. J. 2001. *Rainfall-Runoff Modelling: The Primer.* West Sussex, U.K.: John Wiley and Sons.

Brady, N. C. 1990. *The Nature and Properties of Soils.* New York, N.Y.: Macmillan.

Bravo-Espinosa, M., W. R. Osterkamp, and V. L. Lopes. 2003. Bedload transport in alluvial channels. *J. Hydraulic Eng.* 129(10): 783-795.

Burden, R. L., and J. D. Faires. 2001. *Numerical Analysis.* 7th ed. Pacific Grove, Cal.: Brooks/Cole.

Cochrane, T. A., and D. C. Flanagan. 1999. Assessing water erosion in small watersheds using WEPP with GIS and digital elevation models. *J. Soil and Water Cons.* 54(4): 678-685.

Conroy, W. J. 2005. A coupled upland-erosion and hydrodynamic-sediment transport model for evaluating management-related sediment erosion in forested watersheds. Unpublished PhD diss. Pullman, Wash.: Washington State University, Department of Civil and Environmental Engineering.

Dean, A., and D. Voss. 1999. *Design and Analysis of Experiments.* New York, N.Y.: Springer.

DeLong, L. L., D. B. Thompson, and J. K. Lee. 1997. The computer program FourPT (version 95.01): A model for simulating one-dimensional, unsteady, open-channel flow. Water-Resources Investigations Report 97-4016. Bay St. Louis, Miss.: U.S. Geological Survey.

Ferro, V. 1998. Evaluating overland flow sediment transport capacity. *Hydrological Processes* 12(12): 1895-1910.

Finkner, S. C., M. A. Nearing, G. R. Foster, and J. E. Gilley. 1989. A simplified equation for modeling sediment transport capacity. *Trans. ASAE* 32(5): 1545-1550.

Flanagan, D. C., J. C. Ascough, A. D. Nicks, M. A. Nearing, and J. M. Laflen. 1995. Chapter 1: Overview of the WEPP erosion prediction model. In *Technical Documentation: USDA-Water Erosion Prediction Project (WEPP).* D. C. Flanagan and M. A. Nearing, eds. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.

Franz, D. D., and C. S. Melching. 1997. Full Equations (FEQ) model for the solution of the full, dynamic equations of motion for 1-D unsteady flow in open channels and through control structures. USGS Water-Resources Investigation Report 96-4240. Washington, D.C.: U.S. Geological Survey.

Garbrecht, J., and L. W. Martz. 1995. An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation, and subcatchment parameterization. USDA-ARS Report No. NAWQL-95-1. Durant, Okla.: USDA-ARS National Agricultural Water Quality Laboratory.

Henry, N. 1998. Overview of the Caspar Creek watershed study. In *Proc. Conference on Coastal Watersheds: The Caspar Creek Story*, 1-10. R. R. Ziemer, ed. Albany, Cal.: U.S. Forest Service, Pacific Southwest Research Station.

Jetten, V., G. Govers, and R. Hessel. 2003. Erosion models: Quality of spatial predictions. *Hydrological Processes* 17(5): 887-900.

Keppeler, E., and D. Brown. 1998. Subsurface drainage processes and management impacts. In *Proc. Conference on Coastal Watersheds: The Caspar Creek Story*, 25-34. R. R. Ziemer, ed. Albany, Cal.: U.S. Forest Service, Pacific Southwest Research Station.

Komura, S., and D. B. Simons. 1967. River-bed degradation below dams. *J. Hydraulics Div. ASCE* 93(4): 1-13.

Lewis, J., S. R. Mori, E. Keppeler, and R. R. Ziemer. 2001. Impacts of logging on storm peak flows, flow volumes, and suspended sediment loads in Caspar Creek, California. In *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*, 85-125. M. S. Wigmosta and S. J. Burges, eds. Washington, D.C.: American Geophysical Union.

Lindquist, J., and M. N. Palley. 1967. Prediction of stand growth of young redwood. Bulletin 831. Berkeley, Cal.: University of California, Division of Agricultural Sciences, California Agricultural Experiment Station.

Lisle, T. E. 1995. Particle size variations between bed load and bed material in natural gravel bed rivers. *Water Resources Res.* 31(4): 1107-1118.

McArdle, R. E., W. H. Meyer, and D. Bruce. 1961. The yield of Douglas fir in the Pacific Northwest. Technical Bulletin No. 201. Washington, D.C.: U.S. Forest Service.

McCuen, R. H. 1998. *Hydrologic Analysis and Design.* 2nd ed. Upper Saddle River, N.J.: Prentice-Hall.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models, Part I-A: Discussion of principles. *J. Hydrology* 10(3): 282-290.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2001. Soil and Water Assessment Tool: Theoretical Documentation. Version 2000. Temple, Texas: USDA-ARS Grassland, Soil and Water Research Laboratory.

SAS. 2002. Statistical Analysis Software System, Version 9.00. Cary, N.C.: SAS Institute, Inc.

Schaffranek, R. W., R. A. Baltzer, and D. E. Goldberg. 1981. A model for simulation of flow in singular and interconnected channels. In *USGS Techniques of Water-Resources Investigations*, Book 7, Chapter 3. Washington, D.C.: U.S. Geological Survey.

Toffaleti, F. B. 1968. A procedure for computation of the total river sand discharge and detailed distribution, bed to surface. Technical Report No. 5. Vicksburg, Miss.: U.S. Army Corps of Engineers.

USACE. 1994. Flood-runoff analysis. EM 1110-2-1417. Davis, Cal.: U.S. Army Corps of Engineers, Hydraulic Engineering Center.

USDA-SCS. 1991. Section 4: Hydrology. In *National Engineering Handbook.* Washington, D.C.: U.S. Government Printing Office.

USEPA. 1999. Protocol for developing sediment TMDLs. 1st ed. EPA 841-B-99-004. Washington, D.C.: U.S. Environmental Protection Agency.

USEPA. 2005. National section 303(d) list fact sheet. Available at: http://oaspub.epa.gov/waters/national_rept.control. Accessed 4 May 2004.

Vieira, D. A., and W. Wu. 2002. CCHE1D Version 3.0: Model capabilities and applications. Technical Report No. NCCHE-TR-2002-05. University, Miss.: National Center for Computational Hydroscience and Engineering.

Wang, S. Y., W. Wu, H.-M. Hsia, and C.-C. Cheng. 2002. Simulation of flood and sediment routing in the Pa-Chang River and the Pu-Tze River of Taiwan using CCHE1D model. In *Proc. 5th International Conference on Hydro-Science and -Engineering* (ICHE-2002; Warsaw, Poland). International Association of Hydraulic Engineering and Research.

Wicks, J. M., and J. C. Bathurst. 1996. SHESED: A physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system. *J. Hydrology* 175(1-4): 213-238.

Wu, W., and D. A. Vieira. 2002. One-dimensional channel network model CCHE1D version 3.0: Technical manual. Technical Report No. NCCHE-TR-2002-1. University, Miss.: National Center for Computational Hydroscience and Engineering.

Wu, W., S. Y. Wang, and Y. Jia. 2000. Nonuniform sediment transport in alluvial rivers. *J. Hydraulic Res*. 38(6): 427-434.

Wu, W., D. A. Vieira, and S. Y. Wang. 2004. One-dimensional numerical model for nonuniform sediment transport under unsteady flows in channel networks. *J. Hydraulic Eng.* 130(9): 914-923.

Yalin, M. S. 1963. An expression for bed-load transportation. *J. Hydraulics Div. ASCE* 89(3): 221-250.

Yan, J., and J. Zhang. 2001. Evaluation of the MIKE-SHE modeling system. Southern Cooperative Series Bulletin No. 398. Raleigh, N.C.: SAAESD.

Yang, C. T. 1996. *Sediment Transport: Theory and Practice.* New York, N.Y.: McGraw-Hill.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. Soil and Water Cons.* 44(2): 4522-4561.