US Army Corps
of Engineers
Hydrologic Engineering Center

Use of Land Surface Erosion Techniques with Stream Channel Sedimentation Models

Technical Paper No. 152

March 1996

USE OF LAND SURFACE EROSION TECHNIQUES WITH STREAM CHANNEL SEDIMENTATION MODELS[1]

by

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Abstract: The objective of this paper is to present methods that can be used to estimate the quantity and gradation of sediment produced from a watershed. These values are necessary for mobile boundary hydraulic modeling and other sedimentation studies. These quantities are needed for designing flood control channels, estimating sediment deposition in reservoirs or navigation channels, and evaluating the sedimentation impacts of proposed projects or land use modifications. Considerable information is available for the estimation of sediment yield from a watershed. These methods use both empirical techniques and land surface erosion theory. The same is true for quantifying sediment transport and sorting processes in rivers. This paper focuses on procedures for using land surface erosion computations to develop the inflowing sediment load for a river sedimentation model, specifically, HEC-6.

Included herein are the results of an assessment of numerical models for the prediction of land surface erosion (HEC, 1995). It was concluded from this assessment that these models have not yet evolved from the experimental/developmental phase to routine engineering use. Therefore, this paper presents a suggested strategy for the use of several traditional methods of computation of land surface erosion to prepare inflowing sediment loads for the operation of HEC-6.

INTRODUCTION

Considerable information is available on estimating the sediment yield from a watershed using both empirical methods and land surface erosion theory (Haan et al., 1994; Barfield et al., 1981; Kirby and Morgan, 1980; and Tatum, 1963). The same is true for quantifying sediment transport and sorting processes in rivers.

Sediment production and transport in a watershed are influenced by a complex set of geomorphic processes that vary in time and space. Important erosion processes include soil detachment through raindrop impact and overland flow, rill erosion and transport, gully erosion, channel degradation and bank erosion, various types of surficial gravity erosion, and wind erosion. Other processes that can contribute to the total watershed sediment production may include channel bank and hillslope failures, landsliding, forest fires, and debris flows. Land use practices such as logging and clearing, grazing, road construction, agriculture, and urbanization activities also affect sediment production and delivery from a watershed. Sediment production may vary significantly with long-term cycles in drainage system development and rejuvenation, and zones of sediment production and/or deposition may shift in location with time (e.g. headward movement of nick points and/or channel migration and avulsions).

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[1] Paper presented at the Sixth Federal Interagency Sedimentation Conference, March 10-14, 1996, Las Vegas, Nevada.

Spatial and temporal variations in physical and biological features of the watershed make estimation of sediment yield an extremely difficult and imprecise task. Important variables include soils and geology, relief, climate, vegetation, soil moisture, precipitation, drainage density, channel morphology, and human influences. Dominant processes within a watershed may be entirely different between physiographic or ecological provinces, and may change with time. The problem becomes even more complex when grain size distributions and sediment yield for particular events must be estimated for input to sedimentation models such as HEC-6 (HEC, 1993) and WES-SAM (WES, 1992). At the present time, there is no widely accepted procedure for computing basin sediment yield and grain size distribution directly from watershed characteristics without measured information.

REVIEW OF WATERSHED EROSION MODELS

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is a simple mathematical expression which is the most widely used method for estimating total annual sediment discharge from land surfaces resulting from sheet and rill erosion. The Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) is an altered form of the USLE for applications to single storm events. The USLE is an empirically based lumped parameter model which does not define separate hydrological processes such as rainfall, infiltration, and runoff, or fundamental erosional processes such as detachment by raindrop impact, detachment by flow, and sediment transport and depositional processes. The USLE also neglects channel and gully erosion.

Research in the field of land surface erosion has progressed to focus on the physical processes which influence sediment detachment and transport. Yalin (1963) formed a widely used equation which represents the transport capacity in an erosive model through combining rill and interrill flow. Continuing research on interrill erosive processes such as raindrop impact and sediment delivery by Palmer (1965), Young and Wiersma (1973), Mutchler and Young (1975), and Walker et al. (1977) among others, indicated that conditions of interrill transport differ from fluvial transport in two areas: soil surfaces in interrill areas are generally more cohesive and finer grained than alluvial bed material, and transporting forces are supplied both by flow and raindrop impact in the interrill areas.

The rapid advancements in computer technology over the past 20 years has allowed for the widespread application of state-of-the-art erosion prediction technology. There are many hydrologic models available today that have the capability of simulating sediment discharge, transport, and deposition in a watershed. Combined sheet and rill erosion can be predicted through the use of empirically-based models or physically-based models. An indicator of physically-based models is the subdivision of the surface into rill and interrill areas of separate erosion processes.

Continuing research on the physics of rill and interrill sediment discharge has greatly augmented the understanding of watershed erosive processes. However, the application of physically-based models to large watersheds, for which sufficient sediment yield and runoff data are often unavailable, is not a common practice. Furthermore, the physically-based models contain equations with constants and exponents that must be determined for each watershed, and the subdivision of a large watershed into rill and interrill areas would require an enormous amount of time and effort. In contrast, empirical models require information on topography, soils, precipitation, and land use that can be estimated from maps and simple field surveys. In modeling decisions, care must be taken that the level of detail of the erosion processes represented by the numerical model and field data is commensurate with the objectives of the application. A summary of the models reviewed (HEC, 1995) is provided in Table 1 below.

Table 1
Comparison of Land Surface Erosion Models

Model Characteristic / Model Name	SP	AGNPS	RUNOFF	WEPP	KINEROS	KYERMO
Proprietary	No	No	No	No	No	No
User's Manual available	Yes	Yes	Yes	Yes	Yes	--
Computer needs	PC	PC	PC	PC	PC	PC
Current version number	--	3.65	3.0	91.5	--	--
Most recent update	3/89	6/92	6/92	9/91	5/89	7/87
Single event yield analysis	Yes	Yes	Yes	Yes	Yes	Yes
Average annual yield analysis	No	No	No	Yes	No	No
Division of watershed into subbasins	No	Yes	Yes	Yes	Yes	Yes
Raindrop impact detachment	No	No	Yes	Yes	Yes	Yes
Rill and interrill erosion processes considered separately	No	No	No	Yes	Yes	Yes
Rill formation processes modeled	No	No	No	No	Yes	Yes
Channel transport/deposition	No	Yes	Yes	No	No	No

ESTIMATING SEDIMENT SOURCES

Table 2 lists sediment yield estimation techniques that may be considered for particular applications. The table includes several empirical computation methods, two comparative methods (aerial photography and topographic surveys), and three regional relationship methods (Dendy and Bolton, 1976, Strand and Pemberton, 1982, and Natural Resource Conservation Service (formerly the Soil Conservation Service) (NRCS). Yield Rate Maps and local or regional soil loss/yield rate estimates from soil and water conservation agencies). The gray areas in Table 2 indicate the physical types of erosion addressed by the individual methods. The blocks marked with an asterisk indicate the types of events to which the methods can be applied.

Table 2
Sediment Source Estimation Techniques

Method	Sheet and Rill Erosion	Gully Erosion	Channel Bed and Bank Erosion	Mass Movement	Average Annual Yield	Single Event Yield
USLE					*	
MUSLE						*
RUSLE					*	
PSIAC					*	
Aerial Photography					*	*
Topographic Surveys					*	*
Thompson or SCS TR32					*	
Dendy and Bolton					*	
Strand and Pemberton, USBR					*	
SCS Yield Rate Map					*	

GENERAL PROCEDURE FOR ESTIMATING SEDIMENT YIELD

Potential methods for estimating sediment yield in ungaged catchments include: (1) application of regression equations based on detailed basin characteristics like rainfall intensities, soil properties, ground cover, etc., (2) use of regional relationships based on global basin characteristics like drainage area, altitude and slope-aspect ratio; (3) transposition of data from similar basins where reliable data are available; (4) integration of annual or single event yields from stream sediment rating curves and flow-duration curves or hydrographs; and (5) application of empirical methods. Any estimate should account for: (1) sheet, rill and interrill erosion from upland land surfaces; (2) gully erosion, stream bed and bank erosion; and (3) mass wasting processes in the basin. In practice, it may be necessary to apply more than one estimation procedure to account for all three. The following general steps are necessary to estimate basin sediment yield. Several of these steps may require iterative applications and adjustment in order to develop reasonable estimates.

(1) Perform field inspection and review of available data. Discuss observations and results from previous studies with local NRCS field office, USGS field survey people, County flood control and channel maintenance personnel, and Corps of Engineers hydrology and hydraulics personnel.

(2) If little or no data are available, prepare a field sampling program to at least collect several bed material and bank material samples from sediment source areas and stream channel locations upstream and through the study area. Perform standard sieve analyses and settling tests on the samples.

(3) Examine published long-term daily discharge records and sediment gage records. The standard procedure used by the USGS is to plot the daily water discharge hydrograph and the daily sediment concentration graph, then integrate them as prescribed by Porterfield (1972). Results from this exercise are expressed in tons/day. Before comparing sediment yields, the period-of-record data should be examined for homogeneity. Adjustments for upstream reservoirs, hydrologic record, land use changes, and farming practices may be necessary before the correlation between sediment yield and water yield can be established.

(4) Develop the daily water discharge - suspended sediment load rating curve from gage data. Integrate the flow duration curve with the measured sediment load - discharge rating curve to develop a good representation of the process-based average annual yield. (Details of how to prepare these curves and compute these values are summarized in (USACE, 1989).

(5) When no field measurements exist, and at least some are required to make dependable sediment yield estimates, a limited sediment sampling program is highly recommended early in the planning phases of the study. This level of short duration sampling is often referred to as "flood water sampling." Caution is necessary, however, because the short record data set will not necessarily provide a representative sample of watershed processes for the full range of possible hydrologic conditions. Therefore, these data are less dependable than the flow duration sediment discharge rating technique. The lack of large flood data may bias the yield results.

(6) Apply several regional analysis procedures (Tatum, 1963, Dendy and Bolton, 1976, and PSIAC, 1968) to estimate average annual yield. Compare the results to published information or reports obtained from other studies in the area. Compare the yields by plotting yield vs. drainage area. Attempt to establish upper and lower bounds on the yield - drainage area curve for low, average and high sediment production years (MacArthur et al., 1990). Use this range of yield values during sediment load sensitivity studies.

(7) Use one or more yield estimating equations to estimate the average annual and single event sediment yields for a range of events (e.g., USLE, RUSLE, PSIAC, MUSLE).

(8) Multiply your gross sediment yields by an appropriate sediment delivery ratio (SDR) if necessary to give the net sediment yield at the project location. For more information on how to estimate the sediment delivery ratio and when to apply it, refer to (USACE, 1989) and (Haan et al., 1994).

(9) A quick method for estimating single event sediment yields involves application of several reliable "annual yield" estimating methods to establish the average annual yield first. Then, assume that an equivalent amount of sediment to the average annual yield occurs during a 2-year event. Also assume that greater single event yields can be approximated by the linear extrapolation of the annual value by multiplying the annual yield by the ratio of the peak single event water flow to the 2-year flows.

$$\text{Yield}_i = \text{Yield}_{AvgAnn} * Q_i/Q_2$$

where Yield_i is the single event yield for an i^{th}-year storm event and Q_i is the peak water discharge for the i^{th}-year event.

This method is only recommended as a procedure for establishing rough estimates of single event yields and for cross-checking values developed by other methods.

(10) Another procedure for estimating single event and average annual yields is through the application of the MUSLE single event yield method. Use the MUSLE procedure to develop single event yield estimates for the 5-, 10-, 50- and 100-year events. Convert the single event sediment yields to an average annual value (if applicable) by integrating the sediment yield vs. probability curve. Compare this value with observed reservoir annual yield data and/or computed annual yield values. Select the most reliable value for annual yield. A detailed example is presented in (HEC, 1995).

(11) Decide whether gully, stream bank erosion or mass wasting processes are active in your study basin. Determine whether your selected annual and single event estimating procedures adequately account for these processes. No generalized analytical procedures are presently available to explicitly calculate these types of sediment production for the full range of possible events. Measured data are obviously the most reliable source to use; otherwise application of empirical relationships and the careful examination of pre- and post-flood event photographs are necessary.

When time, data, and budget permit, process-based erosion and yield models can be used to develop average annual and single event yields. Application of process-based erosion and yield models is generally complex and requires detailed data collection for development of model input parameters and calibration.

ESTIMATING SEDIMENT DISCHARGE CURVES AND GRAIN SIZE DISTRIBUTION RELATIONSHIPS FOR USE IN MOBILE BOUNDARY MODELS

The following sequence of study components was prepared from our experiences with HEC-6 applications and other types of sediment and river engineering investigations.

(1) Collect representative bed material sediment samples through the project reach (USGS, 1978). Develop grain size distribution curves for each bed and bank sample and plot the representative grain sizes (D_{50}, D_{84} and D_{10}) with distance from downstream to upstream.

(2) Develop a sediment gradation curve for the wash load using measured data or watershed soil surveys. If there are no data, apply Einstein's (1950) assumption that the largest representative size present in the wash load is approximately equivalent to the D_{10} of the bed material load. Using this assumption and soil survey data regarding the approximate percentages of sands, gravels, silts, and clays, develop an approximate grain size distribution curve for the wash load fraction of the total load.

(3) Estimate the fraction of the total sediment load that travels as bed material load and the fraction that travels as wash load. One method involves using HEC-6 through an iterative procedure to synthesize its own inflowing bed material load and gradation from the grain size distribution curves measured in the field. Wash load is then computed as the difference of the total sediment yield volume or weight and the HEC-6 estimated bed material load. Another method develops the bed material load by starting with the estimated total sediment load from the computed basin yield. The approximate percentage of bed material load to total load is estimated from information and data measured in the study area. Because there are no established rules of thumb for the ratio of bed material load to total load, one assumes a value based on field observations or measured information and checks to see if that assumption is reasonable (see step number 6). If it is not, new percentages are assumed and checked until the estimated bed material load produces reliable results. Example computations are given in (HEC, 1995).

(4) Develop a composite total load gradation curve by combining the bed material gradation data and curves with the wash load gradation data and curves.

(5) Apply the Corps' SAM procedures (Thomas et al., 1992) to estimate bed form-dependent *n* values. Also utilize SAM to select the most appropriate transport function for a particular river type. Check to see if the river is capable of carrying the estimated single event sediment load using SAM or HEC-6. Determine whether the river through your study reach is "supply limited" during large events or "transport limited." If it is sediment supply limited, channel bed and bank erosion may be important. If it becomes transport limited during large events, sediment accumulation and possible channel avulsion may occur.

(6) Once the total inflowing load curve is complete and an appropriate transport function(s) is selected, use them in HEC-6 or other stream sedimentation models to determine if the estimated load and gradations are in balance with the stream hydraulics and basin yield estimates. If significant deposition or scour occurs in the first few upstream cross sections, then the inflowing load may require adjustment. Once the model performs properly and the computed HEC-6 results appear stable, compare the volumes of total load, bed material load and wash load to observed data. Make adjustments to the load, grain size distribution or transport function according to procedures outlined in the HEC-6 User's Manual, CPD-6, (HEC, 1993) and TD-13 (HEC, 1992).

(7) Perform model calibration and sensitivity studies according to guidelines provided in Chapters 3, 5 and 6 of CPD-6 (HEC, 1993) and Section 3.5 in TD-13 (HEC, 1992).

PREPARATION OF MODEL DATA

Calibration and Performance Testing: Following the development of the basin sediment yield estimates and the necessary model input data, conduct model calibration and application procedures according to Chapters 4 and 5 in TD-13 (HEC, 1992). Check model geometry data for accuracy and completeness, then check the model's ability to duplicate natural river hydraulic conditions for low flow, bank full flow, and high flow. Begin testing using fixed bed computations first, then proceed to movable bed conditions. Apply SAM (WES, 1992) procedures to (a) select the most appropriate transport function, (b) estimate natural channel *n* values linked to channel roughness and bed form. Use methods outlined above to develop the total inflowing sediment load curve and grain size distributions.

Once the total inflowing sediment load curve has been developed, it must be tested to see if the sediment load is compatible with hydraulic conditions of the channel (e.g., sediment transport capacity). If the mobile boundary model, (e.g., HEC-6) computes extreme amounts of scour or deposition at the upstream boundary then the inflowing load curve may not be in balance with the stream and adjustment is required. When this occurs, assume a different percentage for the bed material load, develop a new load curve for HEC-6, and test it again. Be sure the model is numerically stable before adjusting it. Attend to hydraulic problems starting at the downstream end and proceeding toward the upstream end of the model. Reverse the direction for sediment problems. Do not worry about computed scour or deposition problems at the downstream end of the study reach until the model is demonstrating proper behavior upstream from that point.

Check the boundary conditions to determine that the particle size classes in the inflowing load are representative or approximate observed data. Correct any inconsistencies in the load or gradation data and try another execution. If computed transport rates are too high, check the field data for gravel content and determine whether an armor layer is developing. If deposition or scour rates are too high or low, check bank elevations and ineffective flow limits to ensure that the model is not allowing too much overbank flow to create excess channel deposits. Finally, if none of these actions produce acceptable performance, adjust the ratio of inflowing bed material to total load and/or inflowing load curve. Attempt to match observed load data whenever possible.

Sensitivity Testing: During the course of a study it is advisable to perform a sensitivity test. Often, input data such as inflowing sediment load and gradation are not available. The estimating procedures outlined herein can be used to develop load and grain size distribution estimates, but it is important to assess the possible impacts of uncertainties in those values on model results. This simply requires modifying the suspected input data by +/- X% and re-running the simulation. If there is little change in the simulation results, the uncertainty in the estimated data is of no consequence. If large changes occur, however, the input data may require refinement and perhaps field verification (data collection).

CONCLUSION

This work was motivated by the need to provide engineers with tools to develop inflowing sediment load information for HEC-6. The methods suggested represent what we determined are useable and credible at this time. The determination of the size distribution of the sediment delivered to the stream needs more research. Many of the steps in preparation and use of data will continue to be necessary (such as calibration and sensitivity testing) as the technology for computing land surface erosion evolves. We foresee that precipitation-runoff and sediment washoff models will become coupled through the use of digital elevation models and geographic information systems; some systems are currently available that do so. Indeed, one of the components of HEC's NEXGEN software development project is to provide these tools for routine use in hydrologic engineering work.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1996	Technical Paper

4. TITLE AND SUBTITLE
Use of Land Surface Erosion Techniques with Stream Channel Sedimentation Models

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Paper No. 152
(TP-152)

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Also published by the Interagency Advisory Committee on Water Data - Subcommittee on Sedimentation in *Proceedings of the Sixth Federal Interagency Sedimentation Conference*, March 10-14, 1996, Las Vegas, Nevada, pp. IX-17 to IX-23.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The objective of the paper is to present methods that can be used to estimate the quantity and gradation of sediment produced from a watershed. These values are necessary for mobile boundary hydraulic modeling and other sedimentation studies. These quantities are needed for designing flood control channels, estimating sediment deposition in reservoirs or navigation channels, and evaluating the sedimentation impacts of proposed projects or land use modifications. Considerable information is available for the estimation of sediment yield from a watershed. These methods use both empirical techniques and land surface erosion theory. The same is true for quantifying sediment transport and sorting processes in rivers. This paper focuses on procedures for using land surface erosion computations to develop the inflowing sediment load for a river sedimentation model, specifically, HEC-6.

14. SUBJECT TERMS
erosion, sedimentation, modeling, sediment transport

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SCURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	