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SEDIMENTATION, GENERAL*

by

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Abstract. A conceptual model of sediment detachment, transport, and deposition on upland areas and in channels is presented. The model is useful for understanding the impact of proposed land use changes on sedimentation. Papers on sedimentation in an established urban watershed, deterministic modeling of urban sediment discharge, and in-stream settling basins are reviewed. The review comments include emphasis of the papers' major points, examination of some topics from a different viewpoint, and opinions on the usefulness of the proposed methods in design.

Introduction

Sedimentation is a major problem in many urban watersheds. To control sediment, one must consider the watershed as a system, since many processes affecting the sediment regime are interrelated so that a change in one produces a change in another. The papers by Peavy, Curtis, and Kuo consider much of the urban sedimentation system.[1,2,3] Before presenting my review comments of these papers, I will discuss a conceptual model of the erosion-sedimentation system that will be helpful in communicating ideas about the system's behavior.

Conceptual Model

Sedimentation in any watershed involves three basic processes - detachment, transport, and deposition of soil particles. These processes occur on two source areas, - the upland portion of the watershed (areas where overland flow occurs) and in the channel system.

Detachment on Upland Areas

Impacting raindrops and flowing water detach soil particles on upland areas. Rill erosion (detachment by flowing water concentrated in small micro-channels) is most obvious on bare soil and usually indicates large rates of sediment production. Interrill erosion (detachment by impacting raindrop) detaches soil uniformly over the surface and is sometimes called sheet erosion. Interrill erosion may go unnoticed except for its downslope environmental impact, although it can easily erode 40 tons/acre/yr. on a moderately erodible soil exposed to direct raindrop impact.[4]

Detachment is a function of rainfall and runoff erosivity (i.e., their capabilities for detaching soil particles), the soil's susceptibility to detachment by these agents, slope length and steepness, and the influence of land use on these factors. The reader may refer to Meyer and Ports' discussion of these factors elsewhere in these Proceedings as well as to Peavy and to Meyer et al. for practical ways to control upland erosion.[1,5,6,7]

Transport on Upland Areas

Almost all downslope transport of detached soil particles on upland slopes is by overland flow. Obviously, if overland flow can not transport the detached sediment, little sediment will reach the channels. If sediment load exceeds the flow's transport capacity, sediment is deposited. Grass and well-anchored mulch strips, small ponds, concave slopes, and sediment basins reduce the flow's transport capacity and cause deposition, thereby controlling the amount of sediment leaving the area.

Detachment and Transport in Channels

Detachment in a channel depends on flow hydraulics, susceptibility of the channel boundary to detachment, and channel protection; sediment transport depends on flow hydraulics, transportability of the sediment, and availability of sediment for transport. This conceptual model is simplified with respect to the detachment and transport of fine, colloidial size particles that are greatly influenced by water chemistry. Graf and Partheniades thoroughly discussed detachment and transport of fine particles by channel flow.[8,9]

Few, if any, channels with erodible boundaries are stable, particularly if long-term geological processes are considered. Even if a channel is stable, a change in land use in the watershed can upset its stability. For illustration, let's assume a steady discharge. If this discharge has been occurring over a long period, the channel will have

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eroded to a stable cross section, an armor layer will have developed, and vegetation will have stabilized the banks, or the sediment inflow will just equal the stream's transport capacity. It's reasonable to assume that the flow's shear stress (assuming that shear stress is an adequate measure of the flow's capacity to erode) will just equal the critical shear stress required for stability. Changes in upland land use that increase flow rates will increase shear stress above that required for stability. Consequently, the channel will erode until a new armor layer with a larger critical shear stress is exposed, or until the channel widens sufficiently to reduce shear stress back to the stable level.

The channel will aggrade when sediment inflow to the stream from upland erosion exceeds the stream's transport capacity. Sediment is stored in the channel, and may erode after the upland area is stabilized. This extends the impact of a sediment source over a longer time than just when it is actively producing sediment.

A "stable" sand-bed stream is transporting sediment at its transport capacity, which is roughly the amount of sediment being added by upland erosion. Prevention of upland erosion will affect sediment yield little, because the stream will degrade to fill its transport capacity.

In the cases noted above, sediment yield is closely related to flow hydraulics. Sediment rating curves are useful for estimating sediment yields, but they change as flow conditions and sediment availability change.

Sediment yield is independent of flow hydraulics where sediment availability is less than transport capacity. For example, in a stable channel such as a steep concrete-lined drainage ditch, sediment yield depends entirely on upland erosion. Flow hydraulics are correlated with sediment yield only because flow hydraulics are correlated with the hydrologic processes causing upland erosion. However, if the point of interest is sufficiently downstream from the sediment origin that the sediment produced by a storm is deposited in the channel as storm runoff recedes and then if it is reentrained by a later storm, sediment yield is a function of flow hydraulics.

Review Objectives

The above concepts are helpful for tying together the papers of Peavy, Curtis, and Kuo into an interrelated package. Each author has made an important contribution to understanding of the urban sediment control problem. In my review of these papers, I have attempted to highlight some of the papers' major points, to examine some topics from a different viewpoint, and to offer some opinions about the usefulness of the methods in design. Given my comments and the authors' responses, the designer will have a broader base of information.

Comments on "Sedimentation from an Established Urban Watershed"[1]

Overview

Peavy's brief review of sedimentation on urbanizing areas describes the seriousness of the problem. Sediment yield estimates for construction sites have been as high as 20,000 to 40,000 times those from areas of highly erodible soils on steep slopes are often exposed to highly erosive spring and summer rains. Even after the construction areas are stabilized, sediment yields may remain high due to channel erosion from increased runoff in the post-construction period.

Peavy points out that "established" urban watersheds are dynamic and may produce considerable sediment. He defines three categories of sediment production in established urban watersheds as:

> "(1) Sediment loads from post-developed areas with little or no construction activity. (2) Sediment loads from inter-city areas undergoing urban renewal and/or established urban areas undergoing freeway construction. (3) Sediment loads due to increased bank and bottom degradation during channel stabilization."

Peavy reports an 18 month study beginning in 1969 of the discharge of total solids from a 1080 acre watershed in an established area of Durham, North Carolina. The study began during the seeding of a highway construction project in the upper end of the basin.

The basin was divided into six sub-basins, each having more uniform land use than the entire basin. Land use, impervious area, surface characteristics, and average slope data were collected as part of a block by block survey. Streamflow data included flow rates and volumes and concentration of total solids. Higher solids concentrations were noted in the sub-basins where the highway was located.

Sediment transport rate was a function of stream discharge rate. Peavy also found a good correlation between sediment yield for a storm and peak streamflow rate for the storm. The correlation of storm sediment yield with storm runoff was also good, but its correlation with duration of the antecedent dry period, total runoff in the antecedent storm, and antecedent storm peak runoff rate was low (0.3 and less). Using 13 storms, Peavy developed a sediment rating curve giving sediment yield for a storm as a function of peak runoff rate that he used to estimate an average sediment yield of 6.2 tons/acre/year for the study period.

Finally, Peavy notes problems caused by excessive sediment production, and he also discusses several sediment control techniques.

Review Comments

A major point of Peavy's paper is his conclusion that:

> "Recognition of urban sedimentation problems, more use of control technology, and better planning for erosion prevention will be necessary to provide quality streams in urban and suburban environments."

As he points out, several techniques and design procedures are available, but unfortunately the problem and its magnitude are not often recognized or well understood.[10] Sedimentation in either established or developing watersheds obeys the same basic prinidentifying potential sediment sources and the likelihood of erosion and sediment transport. Most control techniques are simple, such as providing a grass strip on a flat slope at the toe of a steep slope, protecting the soil surface with mulch, and using diversions and terraces to prevent large accumulations of flow. Techniques for particular situations can be developed by considering fundamental ways of reducing the potential for erosion and transport.

The sediment control planner should acquaint himself with his system to identify its unique features that are sure to significantly affect sedimentation. Good plans are seldom textbook design; each stituation is unique. The planner needs to inspect his and other designs after installation, looking for successes and failures.

Two factors could affect interpretation of Peavy's Durham study: (1) bed-load was not measured, and (2) the study was short. Depending on sediment properties and flow hydraulics, significant sediment transport could have been by bedload. However, even though total sediment yield would have been higher if bedload had been measured, the qualitative findings would probably have been unchanged.

As Peavy notes, a construction activity may continue to have an impact for several months or years after it ends. Therefore, the 18-month study was perhaps too short to assess the total impact of the highway construction in the Durham study. Attempts to analyze the data raise the questions: Was there significant sediment stored in the channel due to erosion during construction? If so, was this sediment being "cleaned out" during the study period? What were the conditions of the channels in those sub-basins outside of the construction area? Were they degrading from increased flow rates? Without answers to these questions, it's difficult to really assess whether the sediment yield orginated from the construction activity or from within the channels.

Sediment production is greatly affected by the interrelation of the controlling factors. For example, sediment production on an area where flow from an impervious area drains directly onto a steeply sloping, bare area immediately adjacent to a channel is much greater than that from an area where water from the impervious area is diverted from the steep slope and a grassy, flat area separates the bare slope from the channel. Average steepness is not a good indicator for the slope effect of irregular slopes, since a concave slope will produce significantly less sediment than a convex slope.[11,12] Combinations of land use, impervious area, soil, and slope length and steepness for each sediment source are better indicators of potential sediment yield than average values for these factors expressed separately.

Potential sediment yield of upland areas depends on the likelihood of overland flow transporting sediment to a stream. For example, potential sediment delivery to a channel is great for subbasin E_2 of the Durham watershed (Figure 1 of reference 1) because of the close proximity of the construction area to the channel system. Most likely, drainageways around the construction area were designed to quickly and efficiently remove water which also easily transported the sediment. The impact of construction in sub-basin W_2 should be less because of its greater distance from the channel, unless ... facilities move flow directly to the

channel. High sediment loads in sub-basin E_1 are expected because of steep slopes and poor land use that expose bare soil to impacting raindrops and flowing water.

The existence of a relation between streamflow and sediment transport does not necessarily indicate a cause and effect for reasons discussed earlier. Consequently, sediment rating curves should be used with caution. A rating curve developed before a change in land use may be in great error. Although such curves are satisfactory for short time periods, their accuracy should be periodically rechecked if they are to be used for an extended period.

The lack of a relation between sediment load and previous flow suggests that the Durham channel system is short enough that most of the sediment produced by a storm moves through the system with that storm's runoff. Evidently, not much sediment is deposited in the channel to be moved out by a subsequent storm.

Even though the relationship between total volume of sediment yield and peak discharge was satisfactory, a more complete relationship would include volume of runoff. Runoff volume with peak discharge should reflect the differences between high peak discharge-low volume runoff events vs. low peak discharge-large volume runoff events better than peak discharge alone.

Comments on "A Deterministic Urban Storm Water and Sediment Discharge Model"[2]

Overview

Soil loss and sediment yield estimation techniques are useful for evaluating land use impact and developing appropriate engineering or management solutions to sedimentation problems. The Universal Soil-Loss Equation (USLE) is one such widely used tool. Curtis presents an alternate model which considers the sedimentation and runoff process in detail. It is a fundamental model because of its equations describing basic erosion and runoff mechanics. It is probably the most complete model of this type that has been proposed to date.

The model contains separate equations for: detachment by rainfall and runoff on upland areas, transport of detached soil particles by rainfall and runoff on upland areas, and sediment transport by stream flow. Although the model does not include a channel erosion component, it could be easily included.

Both overland flow and streamflow are described using the kinematic wave equations. These equations and the erosion equations are solved numerically giving flow and erosion information at regular times throughout a simulated event and at regular spatial intervals over the segments used to represent a watershed. The segments are selected so that land use, soil type, and slope steepness can be considered uniform within a segment. A number of segments may be required to describe a particular watershed.

The model considers soil movement over impervious surfaces and accounts for any deposition and subsequent erosion that occurs on these and erodible surfaces. Soil deposited during a storm is assumed to remain unconsolidated during the event.

Curtis demonstrates the model's considerable power and flexibility by simulating sediment discharge from various conditions of imperviousness, detached soil accumulation between storms, rainfall intensity, complex storm patterns, and sediment control measures.

General Review Comments

The Curtis model is different from the widely used Universal Soil-Loss Equation in several respects. For those unfamiliar with either the USLE or the Curtis type models, Table 1 presents a companion that is helpful for understanding the applicability of both methods for estimating sediment production.[2,13]

The parameters of the USLE need not be spatially averaged over a complex watershed and, in fact, should not be. Total soil loss depends strongly on the way that factors combine at different locations in the watershed. The USLE can be used to estimate soil loss on slopes that are nonuniform in slope shape, land use, and soil.[11,12] Total soil loss for a watershed is best estimated by selecting an adequate number of points in the watershed, estimating soil loss at each point based on local conditions, and numerically integrating those values over the entire watershed area. Sediment yield estimates for a complex watershed, may be obtained by applying transport factors to route the locational soil losses through the watershed.[15]

Several fundamental models of the detachment-transport-desposition process have been proposed in the last 10 years including convolution and stochastic models as well as deterministic ones.[16,17] The deterministic models vary from the lumped Hydro Comp (Stanford watershed model) approach to the distributed approach used by Curtis.[18,19,20] The lumped approach is better suited to large watersheds where the impact of a local feature is small at the watershed outlet. Within a given type of model, various models often use slightly different overland flow and erosion equations and solution techniques.

The designer should consider the following points in selecting a model. (1) The model should do what the designer wants it to do, and he should use the model as it was intended to be used (i.e. don't expect an average annual model to be adequate for single storms). (2) Parameter values must be available or obtainable within the available resources. (3) The designer should feel comfortable using the model because a less accurate model wisely used is better than an accurate model blindly used. (The designer should not use this as excuse for not educating himself on unfamiliar models.)

Most of the fundamental models, including the Curtis model, are still in research and development, which limits their usefulness for making quantitative design estimates. However, they can be quite helpful for studying the relative impact of land use changes on sediment production in situations where evaluation is difficult even when a substantial data set is available as illustrated by the difficulty in interpreting Peavy's data. However, if these models are to approach the utility of the USLE, parameter values must be easily obtainable for ungaged conditions based on readily available hydrologic, land use, topographic, and soils information.

Specific Review Comments

Mathematical models are based on conceptual models of the sedimentation process that vary with the modeler. For example, I prefer separating upland erosion according to source of sediment, i.e., rill and interrill erosion. This approach directly parallels dividing watershed sediment production into the channel and upland phases.[4,21] Curtis separates according to processes, i.e., detachment by rainfall, detachment by flow, transport by rainfall, and transport by flow. While these subtle differences are important to the researcher, they may not have much practical significance. However, inclusion, in some form, of separate equations for detachment by flow, detachment by rainfall and transport by flow greatly increases the flexibility and

Table 1. Comparison of Universal Soil-Loss Equation with the Curtis Model.

USLE	CURTIS MODEL
1. Working design tool with readily available parameter values.	Still in research and development; parameters values not readily available particularly for ungaged areas.
2. Estimates soil loss on upland areas only; does not estimate deposition.	Estimates upland soil loss and deposition and channel transport and deposition.
3. Does not estimate channel or gully erosion.	Could estimate channel and gully erosion with expansion.
4. Capable of estimating soil loss on complex watersheds where soil, topography, and land use vary with location.	Capable of estimating both soil loss and sediment yield for complex watersheds.
5. Sediment yield estimates require multiplication by delivery ratio values which are not well defined.	Sediment yield estimates are obtained directly without having to use delivery ratios.
6. Estimates long term average annual or seasonal soil loss; not accurate and not recommended for estimating soil loss from single storm events.*	Estimates sediment discharge for single storm events and gives temporal variation during event; long-term variability effects may be simulated using historical or synthetic rainfall and land-use patterns.

*Although the USLE is not recommended for estimating soil loss from single storms, significant improvements can be obtained by replacing the R factor with $(15Vq_p^{1/3} + 0.5EI)$ where V = volume of overland flow in inches, q_p = peak overland flow runoff rate in inch/hour and EI = storm erosivity as defined for the USLE.[14]

potential accuracy of the Curtis and similar models for estimating soil loss for single storm events in comparison with the USLE, which lumps rill and interrill erosion together.

Curtis' erosion equations can be expanded to illustrate how his model reflects the effect of erosion control practices. The equations for detachment and flow transport can be rewritten as:

$$d_R = C_{DR} K_{DR} I^2 \quad (1)$$

$$d_F = C_{DF} K_{DF} S^{2/3} q^{2/3} \quad (2)$$

$$T_F = C_{TF} K_{TF} S^{5/3} q^{5/3} \quad (3)$$

Here d_R and d_F are detachment rates per unit area at a location by rainfall and flow, respectively; T_F is the flow's transport capacity, (rainfall's transport capacity is neglected); K_{DR} and K_{DF} are soil erodibility factors, K_{TF} is a soil transportability factor (function of particle fall velocity, diameter, density, etc.); C_{DR}, C_{DF}, and C_{TF} are management factors that are a function of land use; S is slope steepness, and q is the per unit width discharge rate. For example, the C factors are 1 for no erosion control; for mulch, they are functions of mulch type and rate. The factor C_{DR} has been taken as the fraction of the soil surface left exposed to direct raindrop impact at a given mulch rate (e.g., $C_{DR} \approx 0.3$ for 1 T/A straw) and C_{DF} has been related to mulch's effect on flow velocity (e.g., $C_{DF} \approx 0.08$ for 1 T/A straw).[21] If mulch fails because of mass movement or rilling underneath allowing increased rill erosion, the C_{DF} factor increases to perhaps even 1 (the value for no control) depending on the extent of failure. Rough plowing reduces C_{TF}, cutting and filling slopes increases or decreases S, and installing diversions reduces q. Values of K are affected by the type of soils left exposed.

Curtis illustrates the great potential of his model for analyzing alternative control practices. This can be further demonstrated by rewriting his Table III in terms of equations 1-3, above, to give the values shown in Table 2. (See Figure 1 herin.) Rainfall transport is assumed small and is therefore neglected.

Soil transportability K_{TF} is the same for all segments because detachment on all segments is assumed to produce the same size and density particles. Taking C_{TF} as being the same for the smooth concrete surface as for the soil surface implies a very smooth soil surface with no depressional sediment storage.

Table 2. Detachment and Transport Parameters.

Segment	Flow Detachment		Rainfall Detachment		Flow Transport	
	C_{DF}	K_{DF}	C_{DR}	K_{DR}	C_{TF}	K_{TF}
S2	1.00	0.00	1.00	0.00	1.0	10.0
C2	1.00	0.00	1.00	0.00	1.0	10.0
OF4	1.00	0.10	1.00	0.01	1.0	10.0
VS	0.25	0.10	0.75	0.005	0.5	10.0
OF5	1.00	0.10	1.00	0.01	1.0	10.0
OF6	1.00	0.10	1.00	0.01	1.0	10.0

Note that the K values and not the C's are zero for nonerodible, impervious surfaces. The C's are reduced by material on the surface or by a rough surface that absorbs a part of the energy of flow and rainfall. Thus for a bare street, C_{DF}, C_{DR}, and $C_{TF} = 1$. The C values of 1 for segments OF4, OF5, and OF6 represent no cover, i.e., bare soil. The C values for segment VS are estimated to be roughly equivalent to 1/4 tons/acre of straw mulch. Equal K_{DF} and K_{DR} for the various erodible segments reflects a uniform soil.

The VS segment in Figure 1 (Curtis' Figure 14) was ineffective for reducing sediment discharge because it did not reduce transport capacity sufficiently to induce deposition. Since there was no deposition, the reduction in total sediment yield was small because the segment size was small in comparison to the others, even though there was a significant reduction in detachment on VS. The VS practice applied to the entire area would have reduced detachment and thus sediment discharge by about 40% providing the slope length and steepness

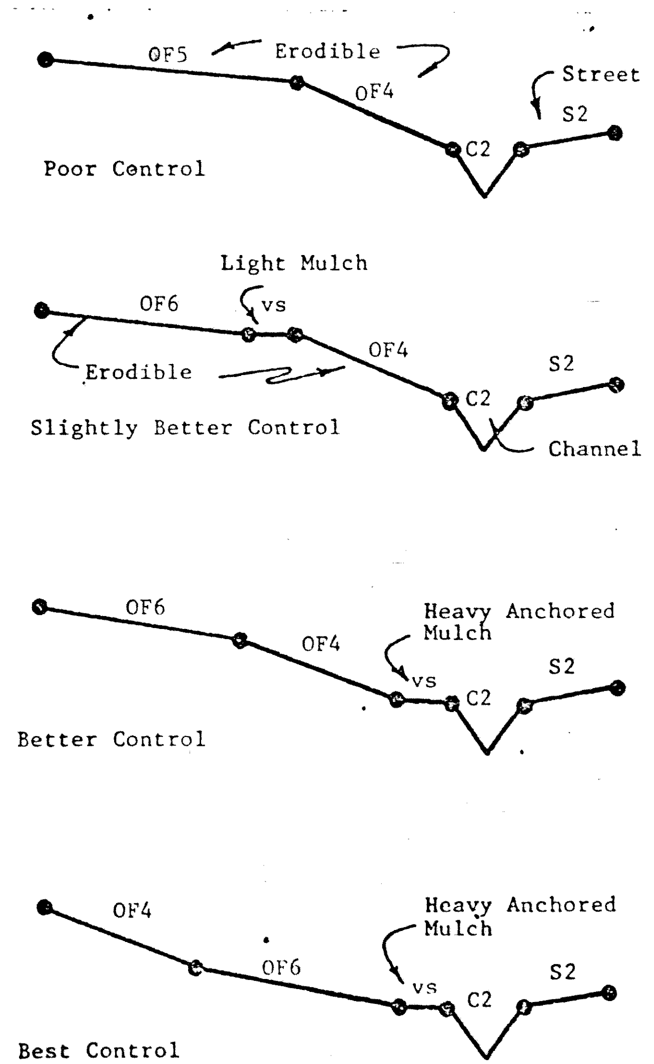

Figure 1. Alternative Erosion Control for a Particular Situation. (Adapted from Curtis' Figure 14.)

were not great. Such low mulch rates are likely to fail and allow serious erosion if slope length and steepness exceed critical values which would be relatively small for this low mulch rate.

Moving VS to the downstream end of OF4 and increasing the mulch rate to 3 tons/acre should greatly decrease sediment yield. This would decrease C_{TF} to 0.05 which should induce deposition in the straw mulch and just upslope of the mulch in the small pond created by the mulch's greater hydraulic resistance compared to the bare soil. Moving VS to the end of the slope traps sediment that otherwise goes directly into the channel. Moving the steepest segment to the upper end reduces sediment yield further.

Selection of the overland flow segments is critical for accurate evaluation of a proposed land use. The model presently requires that properties affecting erosion or sediment transport be uniform within a segment. For example, if land use, soil erodibility or slope steepness, or both, change along the slope length, at least two or more segments are needed as illustrated by Curtis' Figure 14. Erosion on a convex slope that has a highly erodible soil at its lower end and a slightly erodible soil at its upper end is grossly underestimated by a single segment of uniform steepness and soil erodibility. The lower end segment of a concave slope must not be so long that its steepness would indicate no deposition when in fact deposition should be estimated. Also, segments should not pass over different land uses such as diversions, terraces, or a grass strip at the toe of a bare slope.

Selection of segments is most critical on "small" watersheds. As watershed size increases, local features have much less impact on sedimentation, and consequently they may be lumped and averaged to a greater degree. Furthermore, the effect of channel flow on sediment yield increases as watershed size increases.

Model Refinements

The model, as noted by Curtis, will require development and refinement before it is ready for widespread practical use. Perhaps the greatest need is research to determine parameter values. Possible refinements are discussed below.

The assumption that deposited material remains completely unconsolidated during a runoff event may not be entirely valid for material other than sand, large silt particles, and soil aggregates in the upper two or three particle layers.

In a basic laboratory study of the erosion and deposition of cohesive soils, Partheniades found no continuous deposition-reentrainment of particles like that observed with noncohesive soils.[9] Once an aggregate was deposited, it quickly became bound to the soil mass and required a significant increase in shear stress for reentrainment. My visual observation of deposition of soil aggregates by overland flow indicates that the process in the field is somewhere between that observed by Partheniades and the totally detached nature of sands. Between storms, particularly if there has been wetting and drying, the deposited soil seems to consolidate although its erodibility may not be as small as that of the original soil. No definite conclusion can be drawn about the extent of consolidation of deposited material or of soil disturbed by tillage since almost no quanitative field data are available.

Regardless of the extent of consolidation, all previously deposited soil is not available for later erosion by flow. Overland flow depositing sediment is broad and shallow covering a relatively wide area while overland flow detaching previously deposited material concentrates in rills having widths which may cover only 10 to 20% of the deposited soil area. If the flow erodes through the deposited sediment to an original soil that is somewhat resistant to erosion, vertical rill erosion decreases and width of the rills increase due to erosion of the rill sides. This is accompanied by a significant decrease in rill erosion rate.

The logic of the model which permits both flow detachment and ~~transport~~ simultaneously needs reexamination. Partheniades' erosion study on cohesive soils indicates that both deposition and detachment do not occur simultaneously and Hjelmfelt and Lenau's analysis indicates that the actual detachment (removal) of unconsolidated material is just that needed to fill the transport capacity.[9, 22] The possible flow detachment-deposition conditions within the context of the Curtis model are given in Table 3. Deposited sediment is being accummulated in conditions 1 and 2 while soil is being detached (removed) in conditions 3 and 4. The value for K_{DF} is based on whether the flow is detaching previously deposited material or whether it is detaching the original soil. The flow detachment-transport interrelationship proposed by Foster and Meyer conveniently handles these conditions by a simple change of a coefficient which is a function of soil erodibility when the flow is eroding and the suspended sediment transport capacity when the flow is depositing.[23, 24]

Comments on "Sediment Routing in an In-Stream Settling Basin"[3]

Overview

Kuo uses a two-dimensional convective-dispersion equation to study the effectiveness of in-stream settling basins for removing suspended sediment from streamflow. Although his analysis is for routing a hydrograph and sediment-graph for a storm through a basin, it assumes a basically quai-steady state. To apply his analysis, the average velocity and sediment concentration in the inflow stream is needed. The assumed velocity distribution in the upstream and downstream channel section from the basin is the often used logarithmic profile. The sediment concentration in the upstream channel is assumed distributed as the power relationship introduced by Rouse for the logarithmic velocity profile.[8]

Kuo assumes that the velocity profile development in the upper basin end is described by the velocity profile for the lower half of a free turbulent slot jet issuing into a semi-infinite fluid. The profiles in the downstream half of the basin are assumed to be a reflection of those in the upstream half. The dispersion coefficient is taken as a function of distance along the basin but not as a function of depth.

Boundary conditions are: (1) no sediment is transfered through the flow surface and (2) the basin bottom is perfectly absorbing, i.e., a particle reaching the bottom is absorbed with no reentrainment. Kuo uses a backward difference scheme generating a set of linear equations which are

Table 3. Possible Flow Detachment and Deposition Conditions on a Slope Segment for a Time Interval.

Condition	Amount Deposited	Amount Detached by Flow	Sediment Available for Transport	Sediment Leaving Location
1. T_F<SEDUP*	(SEDUP-T_F)	None	SEDUP	T_F
2. T_F<(SEDUP+D_R)	(SEDUP+D_R-T_F)	None	SEDUP+D_R	T_F
3. T_F<(SEDUP+D_R+D_F)	None	T_F-(SEDUP+D_R)**	T_F	T_F
4. TF>(SEDUP+D_R+D_F)	None	D_F	SEDUP+D_R+D_F	SEDUP+D_R+D_F

*SEDUP is amount of sediment ariving from upslope, D_R is the amount of sediment detached by rainfall on the segment, and D_F is the amount of sediment detached by flow on the segment.

**Flow erodes just enough to fill the transport capacity.

solved by the method of successive over-relaxation.

The model is used by Kuo to study the distribution of sediment concentration in a basin and basin trap efficiency for various flow, sediment, and basin size characteristics. The results indicate that the sediment concentration profile for 0.001 cm particles becomes very nearly uniform within a short distance from the upstream basin end. Basin trap efficiency is essentially independent of depth for the range of conditions studied. However, as basin length increases, the increase in trap efficiency is great for large size particles while it is negligible for small particles. Similar increases in trap efficiency are noted for decreases in stream discharge rate. Trap efficiency increased from a low of 9% to 97% as particle size increased from clay to sand.

Kuo points out that his analysis is for deep basins where the no reentrainment assumption is valid. When this assumption is not met, he suggests an appropriate boundary condition.

Review Comments - Theoretical Considerations

Use of basic and theoretical principles to describe sediment movement in an urban watershed is an important design aid even though a design method not directly related to the theoretical analysis is used to develop sediment control plans. Theoretical analysis reveal behavioral characteristics of complex systems that cannot always be identified solely from experimental data. The designer may identify trends from theoretical analyses which can be used as a judgment factor in the application of empirical methods.

This is an important application of Kuo's analysis. However, since the analysis does have considerable design potential beyond an illustrative tool, it's worthwhile to determine the model's present strong and weak points.

The validity of the convective dispersion-continuity equation for turbulent flow is well established.[8] Agreement between theoretical estimates and observed measurements have been good to excellent. However, because the equation is so complex, only relatively simple problems have been solved, even with high speed computers. Kuo has made a significant contribution by extending this type of analysis to the relatively complex in-stream settling basin.

A question in regard to most theoretical analyses of this type is determining how closely the actual conditions match those assumed. In this case, the two certainly agree well enough to develop considerable qualitative information but not well enough at the present for use as a main design tool. Although Kuo provides no comparison of calculated vs. experimental, Kersten whose theoretical analysis is almost identical to Kuo's did make a laboratory comparison.[25] His calculated results did not match experimental results as well as expected based on the success of other investigators using the convective-dispersion equation. Similar differences are expected for Kuo's model. But if field data were available to calibrate Kuo's model, a reliable set of design curves could surely be developed.

Several factors can potentially affect the accuracy of Kuo's model. For many smaller streams, flow through an in-stream basin is probably three dimensional, with secondary currents along the sides and at the ends. Also, the sediment is a mixture of particle sizes, whereas the analysis is based on sediment of one size.

Kuo's velocity profile at the upstream basin end is a definite improvement and is adequate from the basin entrance to where the jet reaches the basin bottom. From this point downstream, bottom friction probably influences the velocity profile, and if the basin were sufficiently long, the logarithmic open channel velocity profile should develop. The velocity profile in the downstream part of the basin is probably not affected by flow convergence as much as the upstream profile is affected by divergence. Thus Kuo's reflection assumption about the centerline may not be an accurate description of the basin velocity profiles. On the other hand, good results have been obtained from the analysis of a simpler erosion problem by using the convective-dispersion equation and assuming a uniform velocity at a section rather than the logarithmic profile.[26]

If the velocity profile is logarithmic in the downstream part of the basin, the dispersion coefficient should be a function of y as well as x. However, good results have also been obtained for the erosion problem by assuming a constant dispersion coefficient.[26] This indicates that an assumption of a uniform velocity and a constant dispersion coefficient might be satisfactory for the basin except in the upstream region where Kuo's profile is a definite improvement. As Kuo suggests, verification of the assumed velocity profiles is needed. Such a study should include data from actual field basins where three dimensional flow is probably present.

Modification of the vertical concentration equation (Kuo's equation 13) for clay is probably unwarranted for engineering applications, since others have reported that the distribution is satisfactory for clay.[8]

As Kuo points out, his analysis is limited to deep basins which he finds acceptable for most practical designs. However, practical reasons are presented later herein why field basins can not always be considered deep basins. Therefore, Kuo's equation 14 (equation 4 herein), which permits reentrainments and bottom erosion, is a more appropriate general boundary condition than the perfectly absorbing bottom assumption for a basin which operates over a wide range of conditions. The factor K in Kuo's equation 14 apparently increases as transport capacity increases in the basin.

$$E(\partial C/\partial y) + KV_T = 0 \qquad (4)$$

where: E = dispersion coefficient
C = concentration of suspended sediment
y = vertical distance
V_T = terminal fall velocity
K = parameter pertinent to degree of scouring, deposition or equilibrium

An alternative boundary condition might be specifying the sediment concentration at a reference level close to the bed as a function of flow hydraulics at each x. For uniform flow, this concentration is constant for all x, but because the flow is nonuniform in a basin, it would vary with distance along the basin.[22]

Basin length - L, is evidently critical if design trap efficiency is to be maintained during the life of the basin, especially where the stream is transporting a large bedload and/or easily deposited suspended load. The easily deposited sediment will settle at the basin entrance, thereby effectively shortening the basin. Based on Kuo's Figure 12 (Figure 2 herein) and the fact that trap efficiency for a zero length basin is zero, a critical basin length must exist such that trap efficiency rapidly decreases as basin length becomes less than a critical value. When the basin shortens to the critical length, either it needs to be cleaned or a new one built.

Similarly, there is apparently a critical basin depth such that as basin depth - D, becomes shallower, its trap efficiency decreases rapidly. Knowing this depth is required for either timely cleanout of the basin or construction of a new one.

The figures showing trap efficiency as a function of L/D seem to be dimensional rather than nondimensional as might be implied by Kuo's figures. For example, Kuo's Figure 12, apparently valid only for D=8', can not be used to evaluate the effect of D as suggested by the L/D ordinate. Otherwise, the figure indicates that trap efficiency decreases with increases in depth, whereas Kuo's Figure 11 (Figure 3 herein) shows no effect of depth on trap efficiency (note that Figure 11 is for a particular L and

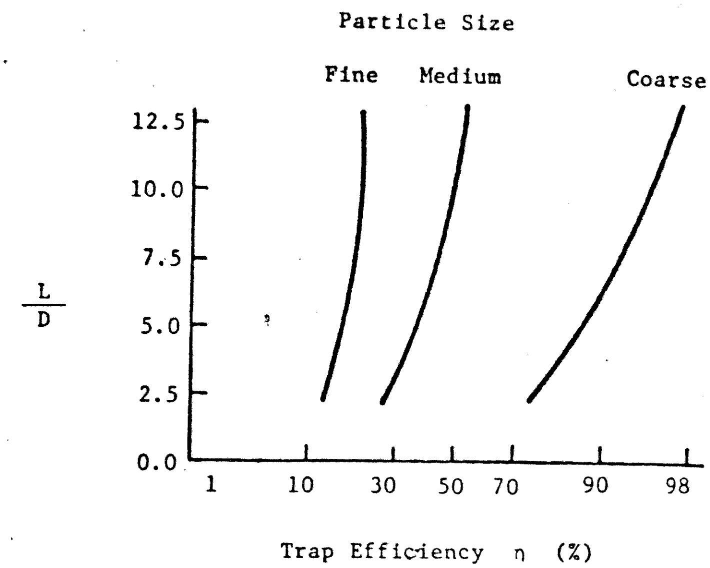

Figure 2. Trap Efficiency vs. Basin Length for Various Particle Sizes (D = 8'). (Adapted from Kuo's Figure 12.)

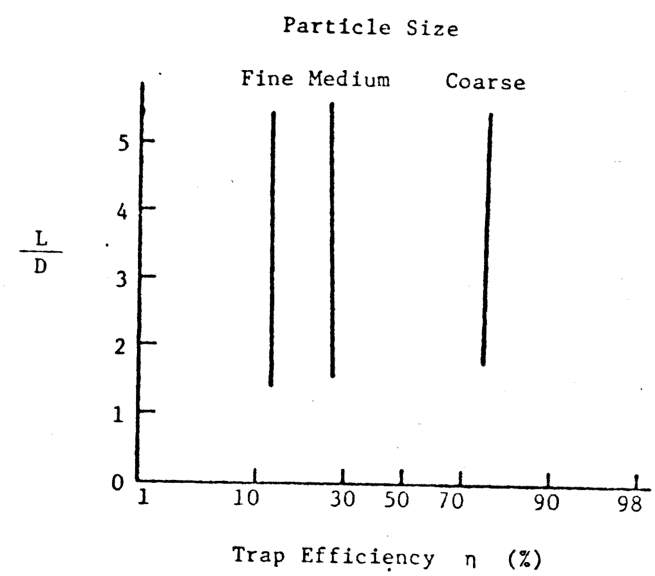

Figure 3. Trap Efficiency vs. Depth of the Drop for Various Particle Sizes (L = 20'). (Adapted from Kuo's Figure 11.)

it does not indicate the effect of L).

Although the simplicity of in-stream settling basins makes them an attractive design alternative, other practices may be more effective for reducing fines in the streamflow. Soil particles are detached from many soils as aggregates with diameters as large as those of coarse sand. Those particles are made up of primary particles (sand, silt, and clay), with the silts and clays being slightly enriched depending on soil type, type of erosion control, and the eroding agents. They are transported and deposited much like large noncohesive particles as long as they are still on the upland area. But once they reach channel flow, mechanical and fluid forces quickly break the aggregrate down to primary particles of sand, silt, and clay. The clay is difficult to deposit once the aggregates disintergrate, releasing the clay. Fines in streamflow can be controlled the most effectively by preventing erosion on the upland areas and in the channel. If erosion can not be eliminated, deposit the sediment as near its original point of detachment as possible by deposition inducing practices such as grass strips, concave slopes, or low gradient water spreaders. Deposition of the aggregates at this point is relatively easy. If deposition on the slope is not feasible, use an on-site sediment trap or basin located as close to the sediment source as possible. Keep the inflow as a broad, thin sheet (not channelized) before it reaches the trap. The objective is to deposit the easily deposited aggregates which contain large amounts of clay before they break down and release the easily suspended clay.

Conclusion

Good design for sediment control requires: (1) a system definition, (2) a qualitative description of the system's behavior (i.e., a conceptual model), (3) design methods based on fundamental principles validated with adequate data, (4) good judgment, and (5) appropriately installed and maintained control practices. The papers of Peavy, Curtis and Kuo apply these design principles and introduce new concepts, findings, and developments that are useful in formulating sediment control plans.

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Tables

Figures

NATIONAL SYMPOSIUM ON URBAN HYDROLOGY, HYDRAULICS, AND SEDIMENT CONTROL
(University of Kentucky, Lexington, Kentucky, July 26-29, 1976)

"COMMENTS ON 'A DETERMINISTIC URBAN STORM WATER AND SEDIMENT DISCHARGE MODEL'--AUTHOR'S REPLY"

by

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Introduction

The reporter is to be congratulated for his efforts in reviewing the paper, "A Deterministic Urban Storm Water and Sediment Discharge Model."[1,2] Foster's rigorous review offers a probing analysis of the paper as well as numerous positive suggestions for possible improvement and refinement of the proposed model. As a result, the communication of information regarding the overall implications and potential uses of the proposed model has been enhanced. The following sections address specific comments raised by Foster.

Expansion of Detachment and Transport Coefficients

The modified Meyer-Wischmeier equations that are basic to the structure of the sediment discharge model are:

$$D_R = S_{DR} I^2 A_S (1.0 - IMP) \quad (1)$$

$$D_F = S_{DF} S^{2/3} [(Q_U^{2/3} + Q_D^{2/3})/2](1.0 - IMP) A_S \quad (2)$$

$$T_F = S_{TR} SI \quad (3)$$

$$T_F = S_{TF} S^{5/3} Q_D^{5/3} \quad (4)$$

where D_R is the soil detachment capacity of rainfall, D_F is the soil detachment capacity of flow, T_R is the soil transport capacity of rainfall, T_F is the soil transport capacity of flow, S_{DR} is the detachment coefficient reflecting soil type and surface conditions, S_{DF} is the detachment coefficient reflecting soil type and surface conditions, S_{TR} is the transport coefficient reflecting soil type and surface conditions, S_{TF} is the transport coefficient reflecting soil type and surface conditions, S is the surface slope, I is the rainfall intensity, Q_U is the flow onto segment at time = t, Q_D is the discharge from segment at time = t, IMP is the decimal fraction of impervious area.

The soil detachment and transport coefficients integrate the combined effects of the physical and chemical properties of the soil as well as prevailing land surface management practices. Foster suggests that these coefficients be expanded to separately account for soil properties and management practices. For example, the flow detachment coefficient, S_{DF}, would be replaced by $C_{DF}K_{DF}$ where C_{DF} is the surface management factor and K_{DF} is a soil erodibility factor. Given the amount of new knowledge resulting from research in progress at various locations on the fundamental mechanics of erosion, the expansion is probably justified. Separation of management and soil factors reduces the amount of "integration" inherent in the single coefficient, allows increased flexibility in the description of prevailing soil and management conditions, as well as providing coefficients that may be more meaningful to the model user.

Particle Deposition

The assumption that deposited material remains unconsolidated during a storm event was questioned. Citing research studies on the deposition of cohesive soils and personal observations, Foster indicated that once an aggregate is deposited, it may quickly become attached to the soil mass and require a higher shear stress for reentrainment.[3]

The erosion-deposition mechanics of cohesive soils are different from sandy unconsolidated soils due to the complex physio-chemical properties of the smaller particles characteristic of cohesive soils. Gravity is the dominant force in the erosion-deposition process of unconsolidated sands due to the relatively large size of the sand particles. However, for the smaller particles associated with cohesive soils, the active surface chemistry of the soil particles and the chemical characteristics of the surrounding water (e.g., nutrient content) can control the erosion-deposition process. For instance, the chemical composition of the water surrounding individual soil particles could affect the rate of particle detachment from the soil mass for a given shear stress and the dispersion of the soil particles once entrainment has occurred.

Foster's point regarding the assumption of deposited soil remaining unconsolidated during a storm event is well taken. However, more research is needed to further quantify the chemistry and physics of eroding cohesive soils before useful mathematical expressions describing the process can be obtained.

Model Logic

Foster has correctly indicated that the model logic which permits both flow detachment and deposition simultaneously needs re-examination. Indications are that flow detachment occurs at a rate that will just fill transport capacity with no surplus flow detachment for deposition.[4] Only a minor change in the computational algorithm is required to meet this condition. Table 1 shows the possible flow detachment and deposition conditions on a slope segment for the corrected algorithm. Computationally, the model establishes a priority for sediment that is available for transport depending on the sediment source. As transport capacity increases, the first sediment to fill transport capacity is incoming sediment from upstream segments followed by deposited

Table 1. Possible Flow Detachment and Deposition Conditions on a Slope Segment for a Time Interval[a]

	Condition	Sediment Available for Transport	Net Detachment	Amount Deposited	Sediment Leaving Location
1.	TRNCAP[b] $\leq$ SEDUP	(DEPOS + SEDUP)	NONE	(SEDUP - TRNCAP)	TRNCAP
2.	TRNCAP $\leq$ (SEDUP + DEPOS)	(DEPOS + SEDUP)	NONE	NONE	TRNCAP
3.	TRNCAP $\leq$ (SEDUP + DEPOS + SNET[c])	(DEPOS + SEDUP + SNET[c])	SNET[c]	(DEPOS + SEDUP + SNET[c]) - TRNCAP	TRNCAP
4.	TRNCAP = (SEDUP + DEPOS + SNET[d])	(DEPOS + SEDUP + SNET[d])	SNET[d]	NONE	TRNCAP
5.	TRNCAP > (SEDUP + DEPOS + SNET[d])	(DEPOS + SEDUP + SNET[d])	SNET[d]	NONE	(DEPOS + SEDUP + SNET[d])

[a]After Foster's table 3.
[b]TRNCAP = $T_R + T_F$ = total transport capacity.
[c]SNET = D_R.
[d]SNET = $D_R + D_F$ where: D_F is equal to that needed to fill TRNCAP, or $D_F = S_{DF} S^{2/3}[(Q_U^{2/3} + Q_D^{2/3})/2](1.0 - IMP)A_S$, whichever is smaller.

material, net rainfall detachment and sediment resulting from flow detachment. This decision process may not be ideal; but, until more is known about the interaction of detachment capacities and the armouring effects of deposited soil, surface water, etc., these assumptions seem reasonable.

Effect of Impervious Area

Although Foster did not directly address the point, some readers may question the results shown in figure VI in the original paper.[1] Figure VI shows the effect of impervious area on sediment discharge by comparing sediment discharges for 0, 25, 50, and 75 percents impervious. The results show that as the percent imperviousness increased the volume of sediment discharge increased. In this test the impervious areas were considered uniformly dispersed throughout the slope segment and the model assumed that the depth of flow was identical for both the impervious and pervious areas. As a result, the effect of increasing flow velocities over the remaining pervious areas more than compensated for the reduced pervious surface area and sediment volume increased.

More realistically, however, as the percent of impervious area increases, so does the amount of impervious area that is directly connected to the drainage system (i.e., channel or sewers). It should be pointed out that the model also has the capability to specify what portion of the impervious area is directly connected and what portion is dispersed throughout the remaining pervious area. In this manner, a more realistic flow regime would result on the pervious area and the sediment discharge volume would be appropriately reduced.

Closure

The writer again wishes to express his appreciation for Foster's review and to the National Symposium on Urban Hydrology, Hydraulics, and Sediment Control for providing a forum for this type of technical dialogue. The opportunity for positive technical discussion from different points of view serves not only to increase the flow of information to the general readership but also to increase the educational value of that information.

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NATIONAL SYMPOSIUM ON URBAN HYDROLOGY, HYDRAULICS, AND SEDIMENT CONTROL
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A DETERMINISTIC URBAN STORM WATER AND SEDIMENT DISCHARGE MODEL

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Abstract. As a catchment is transformed from rural to urban in character, many qualitative and quantitative changes in catchment response to rainfall occur. Citizen and government reactions to these changes have resulted in many new local policies regarding the management of storm waters. These policies place increased emphasis on planning for changes in catchment response and on storm water drainage systems designed to minimize the impact of catchment changes.

One of the problems occurring in an urbanizing region is the generation and subsequent deposition of sediment resulting from eroding soils. Soils laid bare by various construction activities are extremely vulnerable to erosion resulting from direct impact of raindrops and accelerated surface flow velocities. Soil particles enter the drainage system where deposition can occur, thus decreasing the carrying capacity of the system. Diminished carrying capacities coupled with increased quantities of runoff from urban areas can cause serious flooding and related problems. If large amounts of eroded soil reach natural waterways, local stream ecology can be seriously impaired.

A model is presented that utilizes a physically based rainfall/runoff component and a set of relationships describing soil detachment and transport processes to simulate the discharge of sediment from an urban area. The model could be used to help assess the relative impact of proposed watershed changes on the erosion/transport/deposition (ETD) system. Among the concepts that can be evaluated are: land use alternatives, distribution of impervious areas, channel improvements, sediment control practices, infiltration changes, changes in the surface roughness, and changes in slope. Since the model is physically based, it can be used as a tool to gain a better understanding of the physical processes taking place in the ETD system throughout a catchment.

Introduction

It is inevitable that urbanization affects catchment response. Many changes to water resource systems occur as the character of the land surface is altered to accommodate intensive urban activities. The impacts of changes in land use may go beyond the physical boundaries of a particular project. An intricate set of regional impacts may be felt from the social, economic, aesthetic, and environmental aspects of the urbanization process. Of particular interest to water resource specialists is the impact of urbanization on water resource systems.

One aspect of urbanization that is receiving much attention is the problem of soil erosion and sediment discharge. The adverse environmental impacts of excessive soil erosion and subsequent discharge or deposition are well documented. As a result, many local and state governments have enacted legislation directed toward the control of sediment. Engineers are thus required to analyze soil erosion and sedimentation problems and formulate solutions to minimize soil losses.

However, the techniques commonly in use for analyzing the soil erosion and sedimentation problems generally yield little information regarding the actual physical processes taking place. Thus, it is often difficult to analyze the effects of specific changes to the land surface in anything more than a superficial manner.

It may be reasonable to assume that a physically realistic model of the soil erosion/transport/deposition (ETD) system in a catchment could yield information that would improve the evaluation of these impacts and improve the development of appropriate engineering or management solutions. It is the purpose of this paper to present the structure of a model that utilizes a physically based rainfall/runoff component and a set of relationships describing soil detachment and transport processes to simulate the discharge of sediment from an urban area. The model could be used to help assess the relative impacts of proposed watershed changes on the ETD system. Among the concepts that could be evaluated are: land use alternatives, distribution of impervious areas, channel improvements, sediment control practices, infiltration changes, changes in the surface roughness, and changes in slope. Also, since the model is physically based, it could be used as a tool to gain a better understanding of the physical processes taking place in the ETD system throughout a catchment.

Unfortunately, data to adequately verify the model does not yet exist. In fact, the data necessary to verify the model would be difficult and very expensive to obtain. Nevertheless, the need to evaluate various alternative catchment activities with regard to sediment discharge is great, and a computer model incorporating knowledge of the physical processes in the ETD system can be a useful analytical tool.

Background

The most common method of estimating soil loss is the Universal Soil Loss (USL) equation[1]:

$$A = RKLSCP \qquad (1)$$

where A is the annual soil loss in tons/acre, R is the rainfall erosivity index, K is the soil erodibility factor, L is the slope length factor, S is the slope factor, C is the crop management factor, and P is the conservation practice factor. The USL equation is the result of statistical analysis of many years of erosion experiment data and was designed to estimate average annual soil loss from agricultural areas. Modifications to the USL equation have been made to extend its application to construction sites and to the estimation of soil loss resulting from individual storm events.[2,3] However, Wischmeier has recently emphasized the limitations in application of the USL equation to situations other than those the equation was originally intended for.[4]

The USL equation and its subsequent modifications yield estimates of average soil loss per year or per event depending on the particular application. The physical processes taking place in the soil ETD system are not described in detail by the USL equation but time and spatially averaged to form a set of erosion parameters that integrate the effects of individual physical processes.

Some attempts have been made to formulate a rational methodology to temporally distribute estimates of total soil loss.[5,6] These techniques apply the concepts of unit hydrograph theory to develop unit sediment distribution functions. Once an estimate of the total soil loss for a storm event is obtained, a sediment graph showing the time-variant soil loss rates is developed. However, a different set of unit sediment distribution functions of appropriate duration is required at each point where a sediment graph is desired. Thus, the availability of data for the development of the distribution functions is a limiting factor. These techniques also reveal little additional information concerning the actual physical processes taking place throughout the soil ETD system.

In 1968, Meyer and Wischmeier presented a structure for a mathematical model to simulate the process of soil erosion as suggested by W. D. Ellison in the 1940's.[7,8] Ellison observed that the soil erosion process was a process of soil detachment and soil transport by erosive agents. Wischmeier and Meyer formulated relationships that described: 1) soil detachment by rainfall, 2) soil detachment by flow, 3) soil transport by rainfall, and 4) soil transport by flow. The erosion and transport equations are briefly described in the following paragraph.

Detachment by Rainfall

Utilizing the concepts of total rainfall kinetic energy, Wischmeier and Meyer estimated soil detachment by rainfall as:

$$D_R = S_{DR} A_S I^2 \qquad (2)$$

where D_R is the amount of soil detached by rainfall; S_{DR} is a constant reflecting the effects of soil type, land surface conditions, and splash erosion; A_S is the land surface area; and I is the rainfall intensity.

The coefficient S_{DR} tends to account for a variety of physical characteristics of a slope (i.e., soil conditions, micro-topography, vegetal conditions, etc.). However, until more precise mathematical expressions describing these characteristics within the soil ETD system are developed, a coefficient such as S_{DR} will suffice.

Detachment by Overland Flow

The detachment of soil particles by overland flow is represented by the tractive force generated by the moving fluid. The tractive force is proportional to the square of the overland flow velocity; thus, soil detachment by overland flow is assumed proportional to the flow velocity squared. Meyer has also shown that by using Manning's equation and assuming turbulent flow, flow velocity is proportional to $S^{1/3}$ and $Q^{1/3}$.[9] (S is the land surface slope and Q is the volumetric flow rate.) Noting that total soil detachment by overland flow, D_F, is also proportional to the land surface area, A_S, the following relation was obtained:

$$D_F = S_{DF} A_S S^{2/3} (Q_u^{2/3} + Q_D^{2/3})/2 \qquad (3)$$

where S_{DF} is a constant reflecting soil type and surface conditions, Q_u is the upstream inflow to a flow section, and Q_D is the downstream discharge from a flow section.

Transport by Rainfall

The capacity of rainfall to transport soil upon impact is a function of slope, the volume of rainfall, soil properties, micro-topography, and wind velocities. Knowing that soil movement by rainfall splash is proportional to rainfall intensity, I, Meyer and Wischmeier proposed that the transport capacity of the rainfall, T_R, be represented as:

$$T_R = S_{TR} S I \qquad (4)$$

where S_{TR} is a constant reflecting local soil and ground cover conditions.

Transport by Overland Flow

The sediment carrying capacity of water is known to be proportional to the fifth power of the flow velocity, V. Since V previously has been shown to be proportional to $S^{1/3} Q^{1/3}$, the sediment transport capacity, T_F, was represented by:

$$T_F = S_{TF} S^{5/3} Q_D^{5/3} \quad (5)$$

where S_{TF} is a constant reflecting local soil and surface conditions.

Erosion Solution Procedure

The solution procedure as developed by Meyer and Wischmeier for the determination of total soil erosion is represented in figure I.[7]

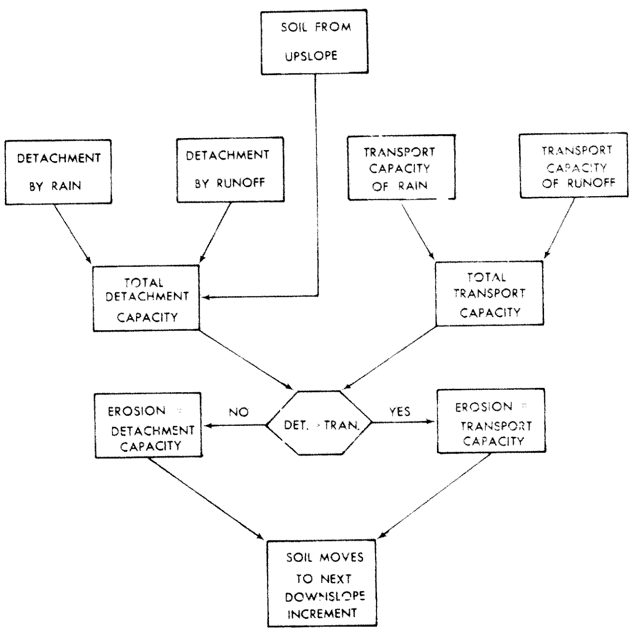


Figure I. Meyer-Wischmeier Erosion Solution Procedure

The total detachment capacity is determined by summing the detachment capacities due to the rainfall and overland flow with the soil influx from upstream segments. It is assumed that sufficient amounts of soil are available to meet the detachment capacity of rainfall and overland flow. Thus, the detachment capacity is numerically equal to the soil that is detached and available for transport.

Total transport capacity is found by summing the transport capacities due to the rainfall and the overland flow. It is assumed that if the total transport capacity is greater than the total detachment capacity (i.e., the total amount of soil available for transport), the total amount of soil eroded in a particular time period is equal to the total detachment capacity. Conversely, if total detachment capacity exceeds the ability of the rainfall and overland flow to transport sediment, then the total erosion is just equal to the total transport capacity.

Meyer and Wischmeier have used equations 2-5 to simulate the movement of soil down a variety of slope-shape configurations. In addition, Kilinc and Richardson have shown support of the functional form of equation 5 as a result of erosion studies conducted at Colorado State University.[10] Equations 2-5, as developed by Meyer and Wischmeier, provide a rational mathematical framework for the continuous simulation of soil movement through a storm event.[7]

Rainfall/Runoff Model

Use of the Meyer and Wischmeier equations to simulate the soil erosion process requires knowledge of the rainfall intensity and the dynamics of the surface runoff. Information regarding rainfall intensity is relatively easy to obtain since rainfall data (either synthetic or observed) are necessary to drive the rainfall/runoff model. If rainfall intensity is available, the information can be used directly. If rainfall volume is available, a volume-time (thus, intensity or rate) relation can easily be obtained. However, many different techniques are used to convert rainfall input to a catchment hydrograph and not all techniques are suitable to physically simulate the soil erosion process. The type of rainfall/runoff model that would best be suited to the Wischmeier-Meyer equations would be one that most realistically represents the physics of surface runoff. Such a description can be obtained by models which describe the runoff process in terms of the underlying principles of conservation of mass and momentum.

The equations of continuity and momentum have been used for many years to describe fluid flow in long rivers. However, in recent years, certain simplifications or approximations to these equations (known as the kinematic approximation) have been used quite successfully to describe overland flows. Owing to the pioneering work of Lighthill and Whitham and Wooding in kinematic wave theory, investigators such as Harley, Schaake, and Woolhiser and Liggett have used kinematic wave theory to describe flows throughout a catchment.[9,11,12,13,14]

The catchment model used in this study is the Deterministic Urban Runoff Model developed by Schaake for the Urban Water Systems Institute of Colorado State University.[13] The model is based on the Hortonian concept of infiltration and uses kinematic wave theory to describe fluid flow in stream channels as well as in overland flow. The following sections briefly describe the model representation of a catchment, kinematic wave theory, and the numerical solution procedure.

Catchment Representation

In a real catchment, the number of alternative flow paths available from the point of raindrop impact to the catchment outfall is extraordinary. To represent the system exactly, a model of enormous complexity would be required. Such a model would be expensive and unnecessarily difficult to use. Thus, many small details must be simulated in the aggregate, while still maintaining the integrity of the dynamics of surface runoff.

The runoff model conceptualizes a natural catchment (figure II) as a set of flow segments (figure III). Each flow segment is considered to have a uniform set of flow parameters (i.e., uniform roughness, infiltration, slope, etc.). The segments are generally described as overland flow segments or as channel segments. Each overland flow segment is an inclined plane of a given slope, surface roughness, and percent imperviousness. Also, the Horton infiltration characteristics are given for the pervious area within an overland

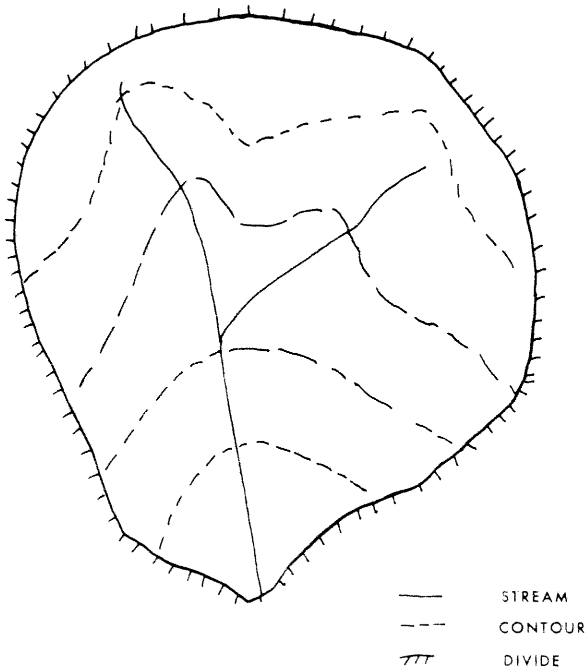


Figure II. Natural Catchment

flow segment. The channel segments are either open channels or closed conduits. The open channels are troughs of triangular or rectangular shape. The closed conduits represent sewer flow and are either rectangular or circular in shape.

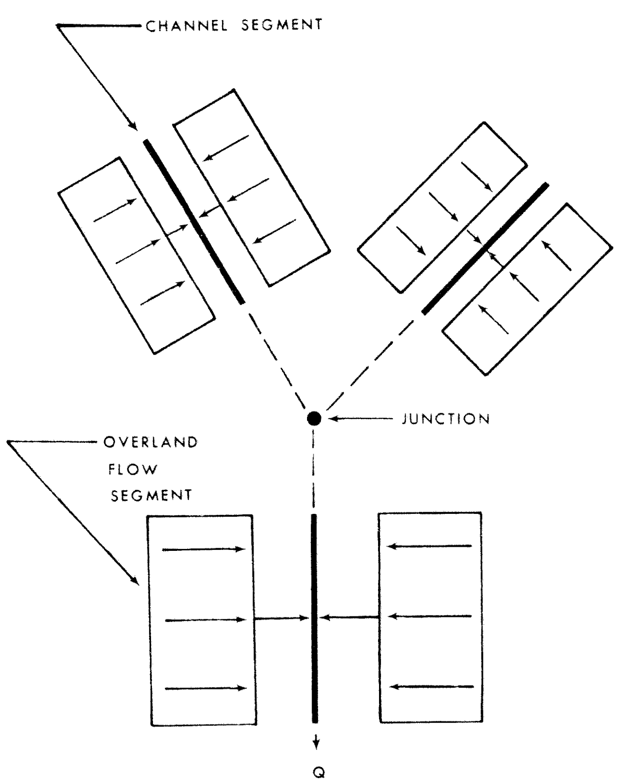


Figure III. Conceptualized Catchment

The model is conceptually simple, but a set of flow segments can be easily arranged into a network that will represent many complex catchments. Also, because the model utilizes segments of inclined planes to represent overland flow surfaces, the Wischmeier-Meyer erosion equations can be used directly to generate soil movement resulting from rainfall impact and surface runoff.

Kinematic Wave Equations

The rainfall/runoff model is based upon the kinematic approximation of the fluid continuity and momentum equations known as the St. Venant equations. The St. Venant equations are:

Continuity Equation

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = q_1 \tag{6}$$

Momentum Equation

$$S - \frac{\partial y}{\partial x} - \frac{v}{g}\frac{\partial v}{\partial x} - \frac{1}{g}\frac{\partial v}{\partial t} = S_f \tag{7}$$

where q is the flow rate per unit width, y is the depth, q_1 is the lateral inflow, S is the channel bottom slope, v is the flow velocity, S_f is the friction slope, and g is the gravitational acceleration constant.

Analytical solutions to equations 6 and 7 are not possible due to the non-linearities in equation 7 and the complex nature of the boundary conditions. The St. Venant equations can be solved numerically and these techniques are well established. However, application of the St. Venant equations to overland flow would require solution on an extremely small scale both spatially and temporally. The resulting computer requirements would be excessive.

Lighthill and Whitham have shown that movement of a flood wave in a river is composed of dynamic and kinematic effects.[9] They also indicated that the dynamic component decays exponentially for Froude numbers less than two. Woolhiser and Liggett have also indicated that the dynamic effects could be neglected if:

$$\frac{SL}{yF} > 10 \tag{8}$$

where S is the channel bottom slope, y is the depth, L is the length, and F is the Froude number.[14] By neglecting the dynamic effects, the momentum equation (equation 7) is approximated as:

$$S = S_f \tag{9}$$

Equation 9 is the steady flow form of the momentum equation, which can also be written as:

$$q = \alpha y^m \tag{10}$$

where α and m are the kinematic flow parameters.

Equations 7 and 10 can easily be solved numerically and are used as the basis for the mathematical description of both overland and channel flows by the model. The kinematic wave equations for an overland flow segment are:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = q_1 = i - f \tag{11}$$

$$q = \alpha_o y^{m_o} \quad (12)$$

where i is the rainfall intensity, and f is the Horton infiltration rate. The quantity i - f is the rainfall excess, and the subscript "o" refers to the overland flow plane.

The corresponding equations for a channel segment are:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_1 \quad (13)$$

$$Q = \alpha_c A^{m_c} \quad (14)$$

where A is the cross sectional area of flow; Q is the discharge rate; and q_1 is the lateral inflow rate of overland flow. The subscript "c" refers to the channel segment.

The kinematic wave parameters α and m can be estimated by Manning's formula. In the case of overland flow:

$$q = \frac{1.49}{n_o} y_o^{5/3} S_o^{1/2} \quad (15)$$

where

$$\alpha_o = \frac{1.49}{n_o} S_o^{1/2} \quad (16)$$

$$m_o = 5/3 \quad (17)$$

In the case of a triangular channel:

$$Q = \frac{1.82}{n_c} \left[\frac{\sqrt{Z}}{1 + \sqrt{1 + Z^2}}\right]^{2/3} A^{4/3} S_c \quad (18)$$

where

$$\alpha_c = \frac{1.82}{n_c} \left[\frac{\sqrt{Z}}{1 + \sqrt{1 + Z^2}}\right]^{2/3} S_c^{1/2} \quad (19)$$

$$m = 4/3 \quad (20)$$

and Z is the channel side slope parameter.

Numerical Solution Procedure

The kinematic wave equations can be combined to yield:

$$\frac{\partial A}{\partial t} + mA^{m-1} \frac{\partial A}{\partial x} = q_1 \quad (21)$$

(Note: Equation 21 could apply to overland flow or channel flow.) This equation has only one dependent variable and can be solved for A in terms of x, t, and q. The model solves equation 21 numerically by replacing the partial derivatives with the appropriate finite difference approximations. The result can be combined with an equation of the form of equation 14 to determine the corresponding discharge, Q.

The numerical solution procedure used in the model has been described elsewhere and will not be discussed in detail here.[15] However, one significant feature of the solution procedure is worth mentioning. To avoid the convergence and stability problems that can occur with particular numerical grid spacings (i.e., the relative sizes of Δt and Δx), two numerical solution procedures are used. The choice of which solution procedure to use is made internally and depends upon the ratio of the kinematic wave speed to $\Delta x/\Delta t$. Together the two solution procedures allow the user to obtain stable and convergent solutions for any arbitrarily chosen Δx and Δt.

Development of Erosion Model

The structure of the rainfall/runoff model allows direct application of the Meyer-Wischmeier equations to the simulation of soil erosion from pervious overland flow planes. With some additional assumptions regarding the movement of soil across impervious surfaces and through small channels, the Meyer-Wischmeier equations are useful in describing soil movement throughout a catchment.

Soil Movement over Impervious Surfaces

It is obvious that no soil could be eroded from surfaces completely covered by asphalt or concrete. However, if soil is discharged from an adjacent pervious area onto an impervious area, soil movement must be accounted for.

Once the eroded soil reaches an impervious surface area, two conditions are possible depending upon local hydraulic conditions. First, if hydraulic conditions permit, the incoming soil will continue in a transport mode. Second, if hydraulic conditions are not sufficient to carry the incoming sediment load, deposition will occur. If it is assumed that the deposited soil remains unconsolidated from one time period to the next, the deposited soil is available for transport during subsequent time intervals. Thus, the total amount of soil available for transport, SAVAIL, over a completely impervious surface is:

$$\text{SAVAIL} = \text{SEDUP} + \text{DEPOS} \quad (22)$$

where SEDUP is the upstream sediment inflow, and DEPOS is the deposited sediment available for transport.

Since the deposited soil was assumed to be unconsolidated, all the soil is "detached" and the detachment coefficients, S_{DR} and S_{DF}, in equations 2 and 3 are effectively zero. The transport coefficients, S_{TR} and S_{TF}, appearing in equations 4 and 5 are non-zero; thus, accounting for the sediment transport over completely impervious surfaces by rainfall and overland flow.

If an overland flow segment is not completely impervious, but is comprised of both pervious and impervious area, the soil detached from the pervious area must also be accounted for. From equation 2 and equation 3 it is seen that the detachment capacities of the rainfall and overland flow are each directly proportional to the surface area of the flow segment. Thus, by modifying the surface area downward to reflect the presence of imperviousness on the flow segment, the respective soil detachment capacities over the pervious portion are:

$$D_R = S_{DR} I^2 A_s (1.0 - \text{IMP}) \quad (23)$$

and

$$D_F = S_{DF} S^{2/3} [(Q_u^{2/3} + Q_D^{2/3})/2](1.0 - \text{IMP}) A_s \quad (24)$$

where IMP is the fraction of impervious area.

Sediment Movement in Small Channels

Many investigators have examined the problem of sediment movement in channels, but the nature of the complex processes taking place is such that no single technique has yet evolved to fully describe sediment movement in channels. Thus, in this study, a simplistic approach was taken to describe the transport capacity of the channel flow.

Soil transported down an overland flow plane will ultimately reach the channel system. If the channel is considered rigid (i.e., roadside gutter, sewer pipe, stable boundary channel, etc.), the total amount of soil available for transport, SAVAIL, in a given channel reach will be:

$$SAVAIL = SEDUP + DEPOS + LATSED \qquad (25)$$

where LATSED is the lateral sediment inflow. Equation 25 is similar to equation 22, except that in the case of channel flow the lateral sediment inflow must be accounted for.

If soil has been deposited in the channel, it is also assumed to be unconsolidated. Thus, the detachment coefficients, S_{DR} and S_{DF}, are effectively zero. In the case of channel flow, the transport capacity of rainfall is assumed negligible; thus, the transport coefficient, S_{TR}, is also zero. The soil transport capacity, T_F, of channel flow is then described by:

$$T_F = S_{TF} S^{5/3} Q_D^{\ 5/3} \qquad (5)$$

Deposited Soil Accounting

Initially, DEPOS is assumed to be zero, but as the solution proceeds, soil accumulates on the flow segment if the amount of soil available for transport exceeds the combined transport capacities of the rainfall and flow. DEPOS continues to increase as long as the available soil exceeds the total transport capacity. Once the transport capacities are sufficient to accommodate all newly detached soil and any soil influx from adjacent areas, DEPOS is reduced in order to meet the transport capacity demand. DEPOS continues to contribute soil to fill the transport capacity demand as long as the supply of deposited soil is available.

As detached soil accumulates on a pervious overland flow surface, the underlying soil becomes more difficult to detach due to the armouring effect of the accumulating cover. Thus, the "actual" detachment will be less than the computed detachment capacities. To account for this process, the model simply assumes that a net detachment capacity, SNET, exists only if the total detachment capacity $(D_R + D_F)$ is greater than the amount of deposited soil on a particular flow segment. Thus if:

$$(D_R + D_F) > DEPOS \qquad (26)$$

then

$$SNET = (D_R + D_F) - DEPOS \qquad (27)$$

On the other hand, no new soil is assumed detached if the total detachment capacity is less than $(D_R + D_F)$. Thus,

$$SNET = 0 \qquad (28)$$

if

$$(D_R + D_F) < DEPOS \qquad (29)$$

The total amount of soil available for transport (SOILAV) during any time period for any segment is thus:

$$SOILAV = SNET + SEDUP + LATSED + DEPOS \qquad (30)$$

Solution Procedure

An algorithm was written utilizing the Meyer-Wischmeier equations to describe the movement of soil over several types of flow segments. These equations coupled with the rainfall/runoff model provide a tool which can be used to gain information regarding the characterisitics of soil movement throughout a catchment. The general solution procedure is shown in figure IV. It is similar to the Meyer-

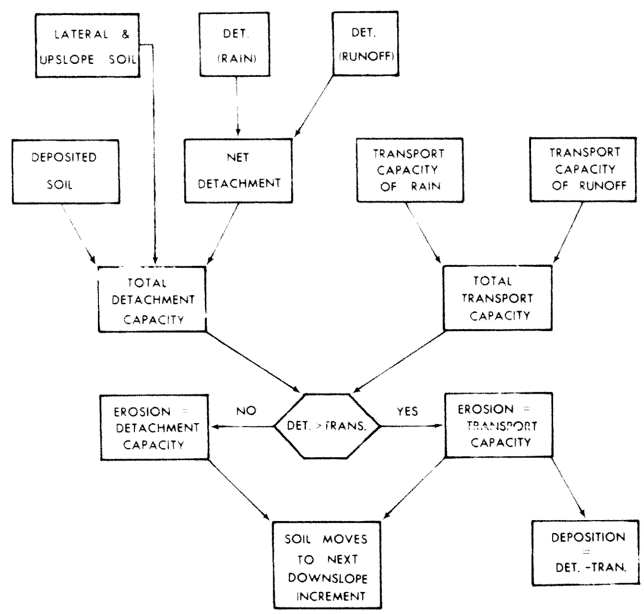


Figure IV. Expanded Meyer-Wischmeier Solution Procedure

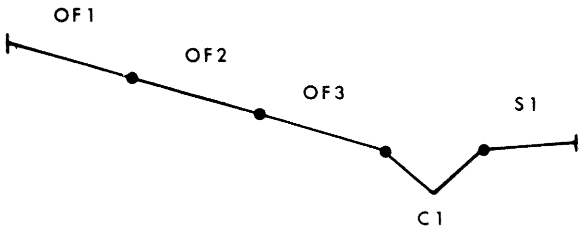
Wischmeier procedure shown in figure I but is expanded to account for segments other than overland flow planes.

The following sections show how the model could be used to describe the effects of various catchment configurations on the soil ETD system.

Model Application

Catchment Description

The first catchment examined is shown schematically in figure V. This relatively simple hypothetical catchment consists of two slopes feeding a single shallow open channel. A total of five flow segments were delineated. (Four overland flow segments and one channel segment.) Segment S1 represents a street section contributing to the channel and is 100 percent impervious. Segment C1 is a shallow triangular channel with



SEGMENT	LENGTH (FT)	SLOPE (FT/FT)
S1	20.	0.01
OF1	200.	0.06
OF2	200.	0.06
OF3	200.	0.06
C1	200.	0.02

Figure V. Test Catchment 1

side slopes of 1.8 percent. The three remaining overland flow segments, OF1, OF2, and OF3, represent flow planes that may undergo some change affecting the sediment discharge characteristics of the catchment. Additional flow segment characteristics are given in figure V and table I. The overland flow segments are all 200 feet wide and the channel segment is 200 feet long. Equation 31 is the Horton infiltration equation used for the pervious areas of the catchment.

$$f = 0.5 \text{ iph} + (3.0 \text{ iph} - 0.5 \text{ iph})e^{-(0.064)t} \qquad (31)$$

where f is the infiltration rate in iph and t is time in minutes.

Table I. Manning's Roughness Coefficients

Flow segment	Percent impervious	n
Overland:	0	0.300
	25	0.229
	50	0.160
	75	0.086
	100	0.015
Channel:	--	0.015

A 75-minute duration was chosen in order that the storm duration would be longer than the catchment time of concentration. The time of concentration, t_c, of the catchment in figure V will vary depending on the surface roughness and rainfall intensity if slope and flow length remain constant. Several steady rainfall rates were used in the study and a limiting condition of an intensity of 1.0 iph with 0. percent imperviousness was used to estimate t_c. Using the kinematic wave nomograph for times of concentration by Ragan and Duru, t_c for the overland flow plane OF1, OF2, and OF3 was computed to be approximately 60 minutes.[17] Thus, 75 minutes would be sufficient to allow the entire catchment to contribute to the outlet before the storm event ends.

Detachment and Transport Parameters

The detachment and transport parameters (S_{DR}, S_{DF}, S_{TR}, and S_{TF}) have yet to be specifically related to catchment characteristics. However, by following the approach of Meyer and Wischmeier, the parameters were assigned values that seemingly gave the appropriate relationship between the physical processes taking place.[7] The values assigned to the parameters showed rainfall effects dominant near the top of overland flow segments and runoff dominant at some point downslope. Near the top of slopes, detachment effects were assumed to dominate while transport effects dominated farther downslope. Since the parameters were subjectively chosen, the sediment discharge values were expressed as "sediment discharge units" and are relative values rather than exact numerical representations. In this manner, the relative effects of proposed alternatives to watershed change could be evaluated. The parameters used for the catchment configuration in figure V appear in table II.

Table II. Detachment and Transport Parameters

Segment	S_{DR}	S_{DF}	S_{TR}	S_{TF}
OF1	0.01	0.10	0.01	10.0
OF2	0.01	0.10	0.01	10.0
OF3	0.01	0.10	0.01	10.0
C1	0.00	0.00	0.00	15.0
S1	0.00	0.00	0.00	0.0

Effect of Imperviousness

The effect of imperviousness on sediment discharge from the hypothetical catchment in figure V is shown in figure VI. Segments OF1, OF2, and OF3 were set to degrees of imperviousness varying from 0. percent to 75 percent. A steady rainfall intensity of 2.0 iph for 75 minutes was used.

The sediment discharge from the catchment increases to a peak at the end of the storm. The discharge of sediment then steadily decreases to zero as the water remaining on the overland flow surfaces and in the channel is drained.

It is expected that the peak sediment discharge should occur at the same time as the peak flow discharge from the catchment occurs. This is seen by examination of the basic erosion equations (equations 2, 3, 4, and 5). For the case of steady rainfall, the detachment and transport capacities of rainfall are constant. On the other hand, the detachment and transport capacities of the flow will vary according to the flow rate, Q. For constant rainfall intensity, the catchment discharge, Q, increases and approaches a peak constant rate as time t reaches t_c and the infiltration rate, f, approaches f_c. Thus, the sediment discharge will follow a similar pattern.

From figure VI it is also seen that the peak sediment discharge, as well as the total volume of discharge (i.e., area under the curves), increased as imperviousness increased from 0. percent to 75 percent. The total amount of pervious area from which soil could be detached decreased with increasing imperviousness. However, increased flow velocities due to reduced surface roughness and increased depths of water on the flow surfaces (due to a lower volume of infiltrated water) produced detachment and transport rates that more

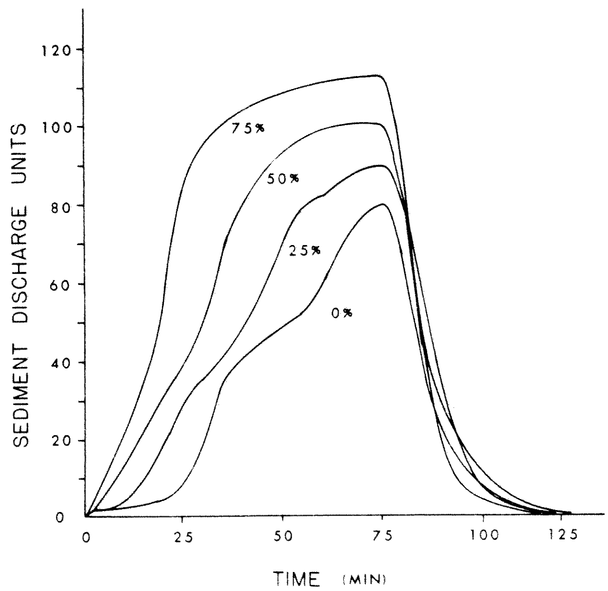


Figure VI. Effect of Impervious Area
(DEPOS = 0 at t = 0)

than compensated for the reduced pervious surface area. Eventually the sediment discharge volume must reach a peak since equation 23 and equation 24 indicate that the detachment capacities of both rainfall and flow must approach zero as imperviousness approaches 100 percent.

Effect of Detached Soil Accumulation Between Storms

For the tests shown in figure VI, it was assumed that no soil was detached and available for transport at t=0. However, for a natural catchment, it can be expected that as soil at the ground surface dries between storms and is disturbed by various activities that may occur on the ground surface, an accumulation of detached soil may be present and available for transport at the beginning of a storm. This is exhibited as a layer of dust on an agricultural field or a construction site. Also, particulate matter may accumulate in street gutters between storms or street cleanings.[18]

To show the effect of detached soil available at t=0, the variable DEPOS (see equation 22) was subjectively set equal to a non-zero value at t=0, and a test was made with the same catchment characteristics used to obtain the results of figure VI. Figure VII indicates that two sediment discharge peaks occured when DEPOS≠0 at t=0. Excess transport capacity was being filled by the additional soil available at t=0. Transport capacity continued to be supplied by "soil in storage" (i.e., DEPOS) until the supply was depleted As the amount of "soil in storage" was reduced and could no longer satisfy the transport capacity, the sediment discharge descreased and approached the sediment discharge rates observed when DEPOS=0 at t=0.

The first peaks shown in figure VII are similar to first peaks sometimes observed on sediment discharge graphs of real catchments.[18] This early peak is often referred to as a "first flush phenomenon" and has been attributed to

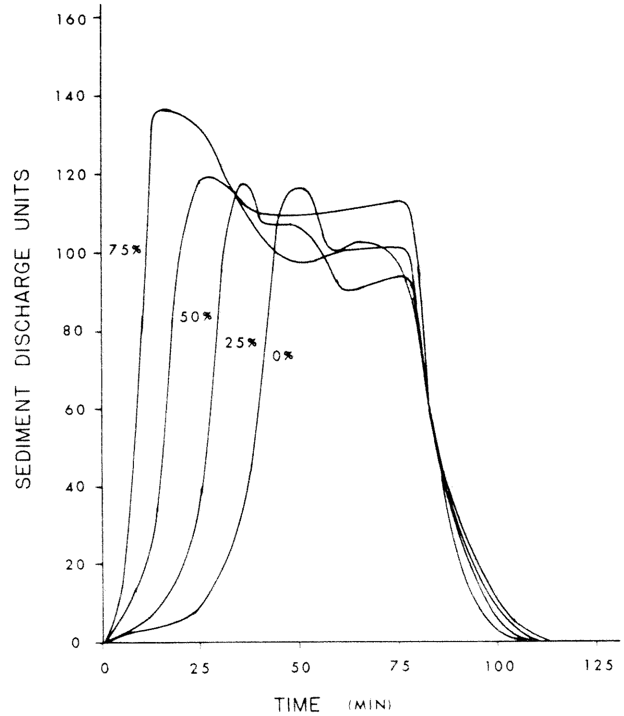


Figure VII. Effect of Impervious Area
(DEPOS ≠ 0 at t = 0)

the flushing of the smaller, more easily transported particulate matter. Larger and heavier particles will be discharged at a later time when transport capacities are higher. Since the equations used in this study are largely insensitive to particle sizes, the occurrence of the double peak was interesting. Although not conclusive, it suggests that first flush phenomena may also be a function of the total volume of soil available for transport at the beginning of the storm.

Effect of Location of Imperviousness

Figure VIII shows the effect of the location of impervious areas on sediment discharge. Three tests were run, each with one of the overland flow segments assigned 50 percent imperviousness and the remaining two segments assigned 0. percent imperviousness. The graphs in figure VIII are

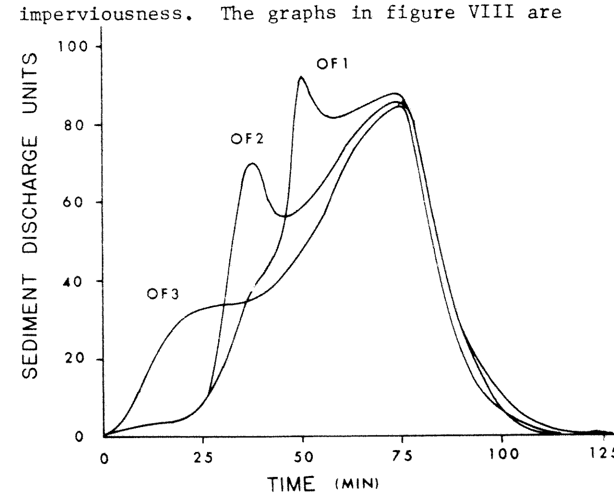


Figure VIII. Effect of Impervious Area Location
(DEPOS = 0 at t = 0)

labelled according to which overland flow segment was 50 percent impervious. The rainfall intensity was a steady 2.0 iph for 75 minutes.

It is again interesting to note that two peaks on the sediment discharge graphs occurred but in this instance DEPOS=0 when t=0. During the early part of a storm, the detachment and transport effects of the rainfall are dominant since the overland flow rates are initially very small; especially on the totally pervious areas where larger volumes of rainfall are lost to infiltration. Thus, soil has an opportunity to become detached and accumulate on segments with low transport capacities.

The segment with 50 percent imperviousness discharges flow almost immediately after the storm begins due to the impervious areas. When this flow is discharged onto adjacent areas that have accumulated detached soil, any excess transport capacity is filled from "soil in storage" as long as the supply lasts. Once the soil in storage is depleted, the sediment discharge curve is controlled largely by the detachment capacities of the rainfall and flow. Similar but more pronounced results are shown in figure IX for the condition when DEPOS≠0 at t=0.

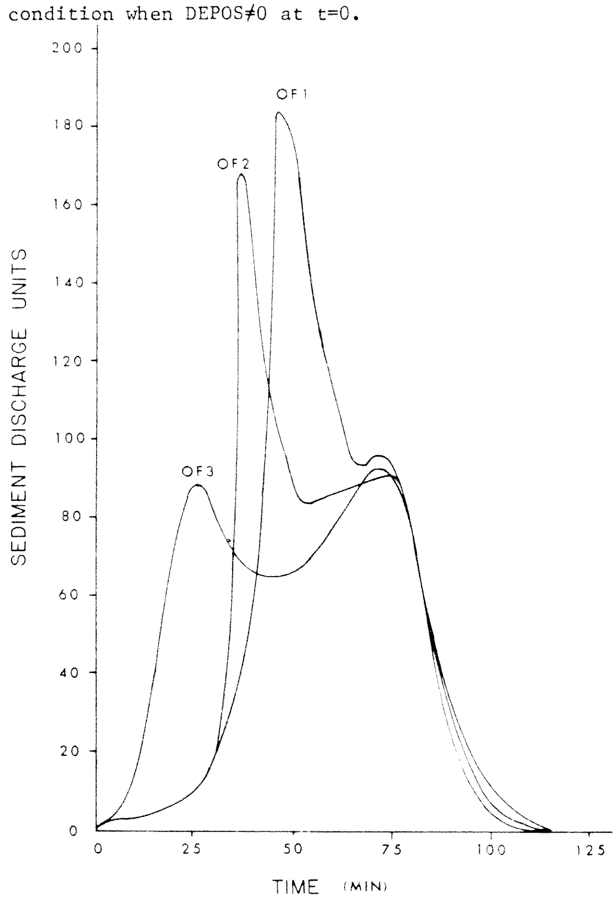


Figure IX. Effect of Impervious Area Location (DEPOS ≠ 0 at t = 0)

The timing and magnitude of the first peak is especially sensitive to the location of the impervious area. The timing of the first peak is largely a function of the distance of the 50 percent impervious segment from the channel. It is obvious that longer travel times are associated with the more distant segments. The magnitude of the first peak is associated with the fact that as distance of the 50 percent impervious area from the channel increases more time is available to accumulate soil (DEPOS) on the pervious segments before the transport capacities increase sufficiently to deplete DEPOS.

The results shown in figure VIII seem to indicate another factor contributing to the occurrence of the first flush phenomena. The configuration and location of various land use activities appear to be important; especially as these activities control the hydraulics of overland flow.

Effect of Rainfall Intensity

The effect of rainfall intensity on the sediment discharge from the catchment in figure V is shown in figure X. Steady rainfall intensities of 1.0 iph,

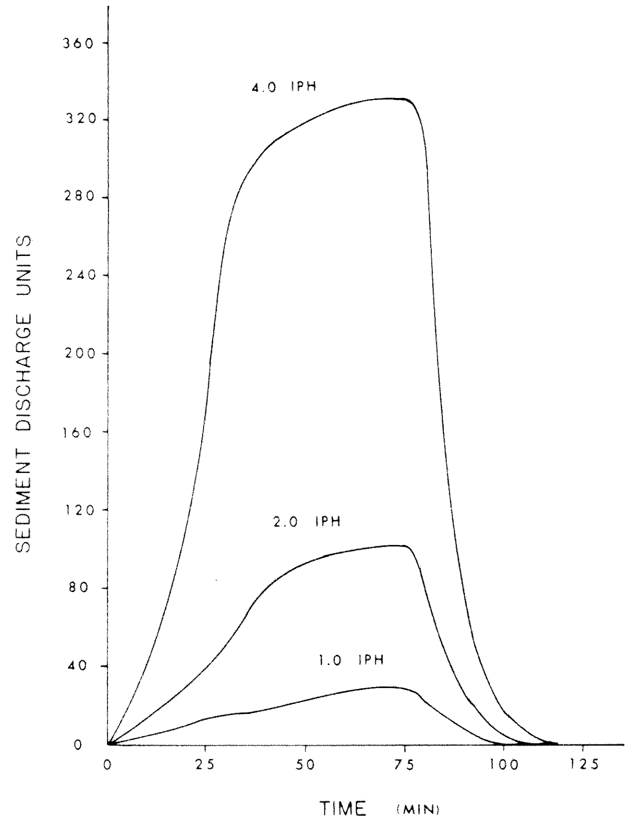


Figure X. Effect of Rainfall Intensity (DEPOS = 0 at t = 0)

2.0 iph, and 4.0 iph for 75 minutes were used. Segments OF1, OF2, and OF3 were assigned 50 percent imperviousness and DEPOS=0 at t=0. The effects are quite obvious and significant as both the peak sediment discharge and the total volume of sediment discharge increased as the rainfall intensity increased.

Similar results are shown in figure XI, where DEPOS≠0 at t=0. The first peak due to the initial available soil was evident, but its shape was affected by the rainfall intensity. At 1.0 iph, the shape of the graph was dominated by the initial availability of detached soil. At 2.0 iph, the initial availability of soil dominated the early portion of the sediment discharge graph while the catchment hydraulics dominated the later portion.

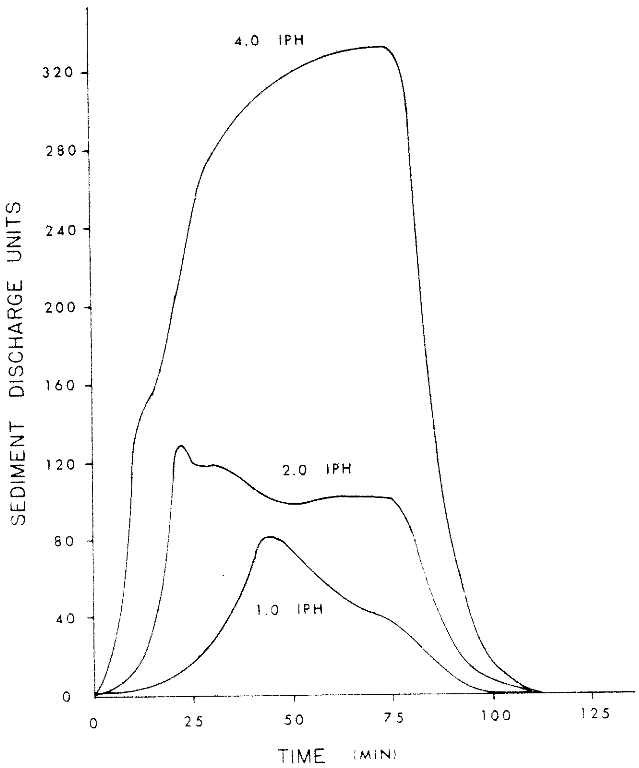


Figure XI. Effect of Rainfall Intensity
(DEPOS ≠ 0 at t = 0)

Finally at 4.0 iph, the initially available soil had little effect on the overall shape of the sediment graph, except to increase the total volume of sediment discharge.

Complex Storm Pattern

The effect of a complex storm pattern on sediment discharge is shown in figure XII (DEPOS=0, t=0) and figure XIII (DEPOS≠0, t=0). Also included in figure XII and figure XIII are the rainfall pattern and the resulting outlet hydrograph from the catchment shown in figure V. Segments OF1, OF2, and OF3 were assigned 50 percent imperviousness.

Figure XII indicates that the sediment discharge graph has approximately the same shape as the outflow hydrograph. This was expected and was indicated earlier from an examination of the basic erosion equations (equations 2-5). It is interesting to note that Swerdon and Kountz assumed a sediment graph of the same shape as the outflow hydrograph in their development of unit sediment distribution functions.[6]

Figure XIII shows the effect of DEPOS≠0 at t=0. Again, for the same rainfall pattern and discharge hydrograph a double peaked sediment discharge graph was observed. The initial supply of soil contributed to the total transport capacity until the supply was depleted.

Evaluation of Sediment Control Measures

The model could also be used to evaluate the effectiveness of different sediment control alternatives. Figure XIV shows two hypothetical catchment configurations. The two catchments are identical, except that a sediment control

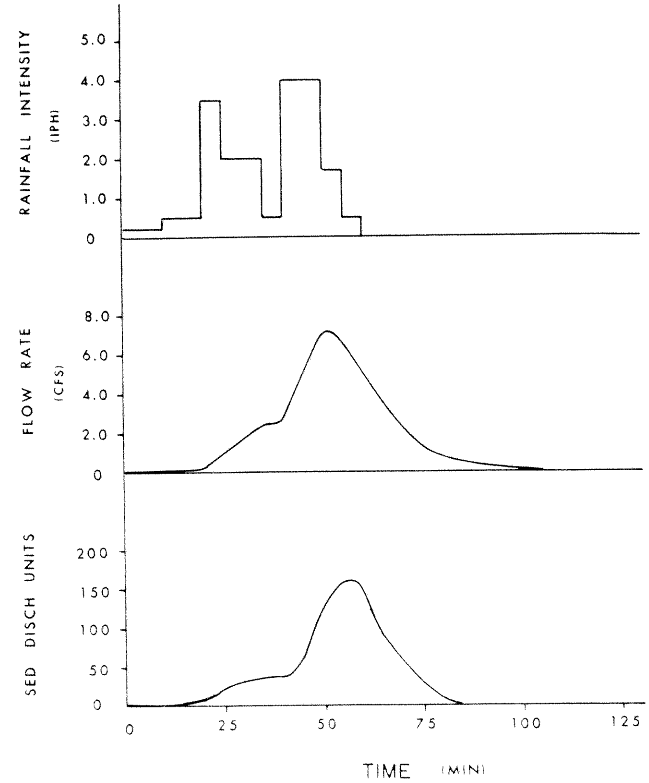


Figure XII. Effect of a Complex Storm Pattern
(DEPOS = 0 at t = 0)

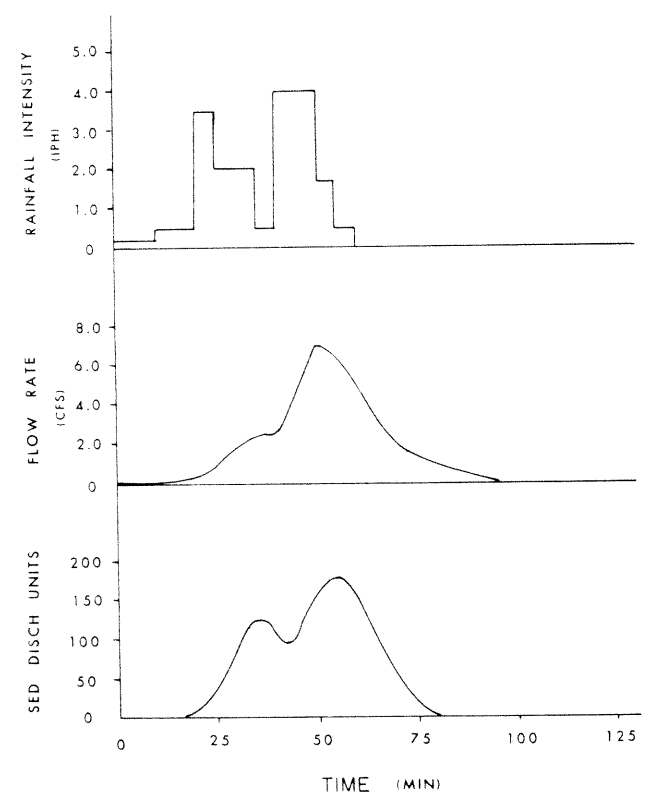
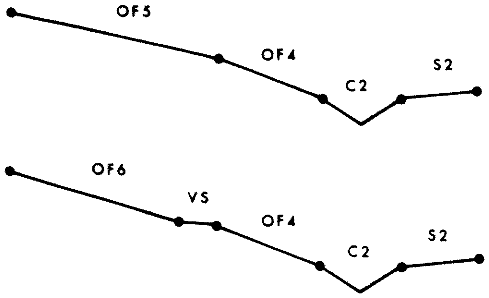


Figure XIII. Effect of a Complex Storm Pattern
(DEPOS ≠ 0 at t = 0)



SEGMENT	LENGTH .FT)	SLOPE (FT/FT)	IMPERVIOUSNESS (%)	ROUGHNESS
S2	20.	0.02	100.	0.012
C2	200.	0.03	-	0.015
OF5	200.	0.04	25	0.229
OF6	180.	0.04	25	0.229
VS	20.	0.01	0	0.500
OF4	50.	0.06	25	0.229

Figure XIV. Test Catchment 2

strip, VS, has been added to one configuration. The sediment control strip was 20 feet long and segment OF5 was shortened from 200 feet to 180 feet to keep the total flow length the same. Figure XIV contains additional information regarding the segment characteristics. All segments are 200 feet wide. A rainfall intensity of 2.0 iph was used. The soil detachment and transport c coefficients used in this test appear in table III.

Table III. Detachment and Transport Parameters

Segment	S_{DR}	S_{DF}	S_{TR}	S_{TF}
S2	0.00	0.00	0.0	0.0
C2	0.00	0.00	0.0	15.0
OF4	0.01	0.10	0.01	10.0
VS	0.005	0.05	0.005	5.0
OF5	0.01	0.10	0.01	10.0
OF6	0.01	0.10	0.01	10.0

Figure XV shows the effect of the sediment control strip on the sediment discharge. The peak discharge was not reduced significantly and the total sediment volume discharge was reduced less than 5 percent. Apparently the rainfall intensity of 2.0 iph for 75 minutes was too high for the sediment control strip to show any pronounced effect. In this case, the sediment control strip may be more effective for lower rainfall intensities. Nevertheless, some effect is apparent and indicates the model's potential for evaluating specific sediment control measures.

Discussion and Conclusions

The storm water and sediment discharge model is flexible and can be applied to a wide variety of catchment configurations and conditions. The model could be used as a tool to help evaluate many management or design alternatives proposed for a particular catchment.

To improve the existing model, several important

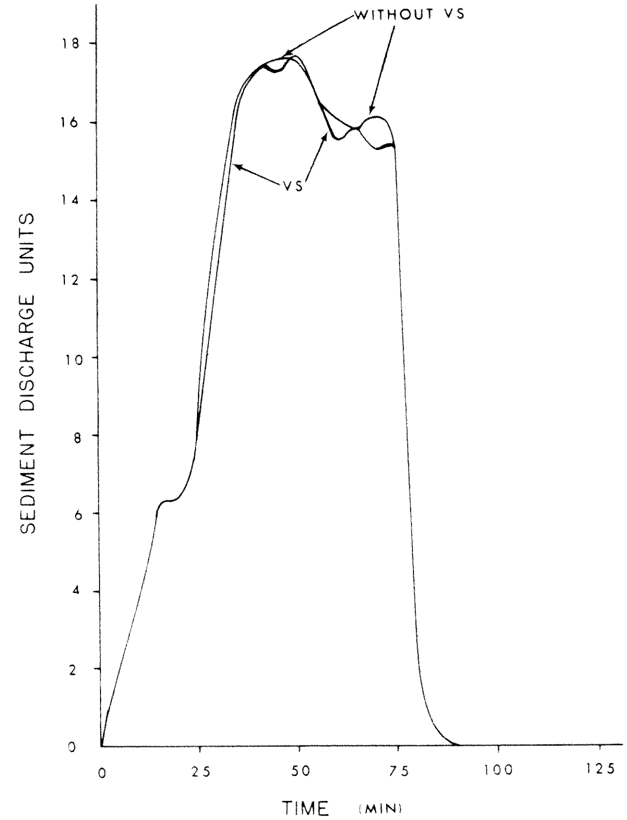


Figure XV. Effect of Sediment Control Strip (DEPOS = 0 at t = 0)

aspects should be addressed. First, a methodology must be developed for relating the detachment and transport parameters to specific soil conditions in a catchment. In this manner, the sediment discharge units would become more physically meaningful.

One approach would be to calibrate the model to observed data from a particular catchment. Then changes proposed to that catchment or to a similar one could be evaluated. However, this approach would restrict use of the model to catchments with an adequate sediment discharge data base.

Another area for further investigation is the establishment of accumulation functions to estimate the buildup of detached soil between storms (or street cleanings in the case of street gutters). Thus, the length of time between "flushing" events (i.e., natural storm or a cleanup) can be studied for its effect on sediment discharge.

The effect of the particle size distribution is also important since transport and sedimentation characteristics of particles vary with size. Foster has developed a modification to the Yalin sediment transport equations to describe sediment transport in shallow flows and may be a promising alternative to the Meyer-Wischmeier transport equations.[19] In addition, Sutherland has used the modified Yalin equations quite successfully to simulate particulate matter transport through urban street gutters.[18] The use of the modified Yalin equation for particle transport would also require particle size sensitive accumulation functions and detachment relationships.

A physically based rainfall/runoff and sediment discharge model has been presented. The model was used to show how a variety of catchment conditions and configurations could affect sediment discharge. The model is conceptually simple but different flow segments could be combined to evaluate specific changes proposed for many complex catchment configurations.

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