Sediment yield estimation and the design of sediment control structures in rural Africa

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ABSTRACT One of the major causes of sedimentation is the removal of the natural vegetative cover of soils. In the last few decades agriculture, urbanization and open-cast mining activities have expanded rapidly in southern Africa. Poor agricultural and development practices have resulted in large tracts of land being denuded of their vegetative cover. This paper discusses procedures for determining sediment yields and presents a computer based technique for determining surface runoff and sediment yields from a rural catchment. Application of the model is discussed and the selection and design of several sediment control measures is outlined.

INTRODUCTION

Land disturbances associated with urbanization, mining, silviculture and agriculture are major sources of sediment. Although erosion rates associated with silviculture, surface mining and urbanization are much higher than from agricultural sources, these activities only occupy a small percentage of the land in most countries. In the USA, more than 50% of the sediment reaching the streams has been attributed to agricultural activities (Environmental Protection Agency, 1976). It is probable that in southern Africa the percentage is even higher and that in overgrazed areas erosion rates approach those of surface mined lands. Soil losses in South Africa have been estimated as over 300 million t year\(^{-1}\) (Roberts, 1983).

Estimation des apports en sédiments et projet d'ouvrages de contrôle des sédiments en Afrique rurale

RESUME La suppression de la végétation naturelle du terrain est une des causes les plus importantes de l'érosion. Pendant les deux dernières décennies, l'agriculture, l'urbanisation et l'exploitation à ciel ouvert se sont développées rapidement en Afrique du sud. Par suite de méthodes défectueuses dans le domaine de l'agriculture et du développement agricole, des étendues immenses ont perdu leurs végétations. Cette étude propose une méthode pour estimer la quantité de sédiment produit, et présente une technique utilisant l'ordinateur pour déterminer le ruissellement superficiel et la quantité de sédiment d'un bassin versant rural. On y discute l'application de ce modèle et on indique le choix et les dispositions de plusieurs mesures à prendre pour contrôler les sédiments.
Sediment from agricultural basins results in losses of valuable topsoil and a reduction in the agricultural potential of the land. High sediment discharges can produce downstream reductions in reservoir storage, increased flooding due to reduced river channel capacities, increased turbidity and downstream pollution by insecticides and fertilizers contained in the sediment laden flows.

This paper outlines procedures for predicting erosion and sediment yields from agricultural basins and presents a computer-based technique for determining surface runoff and sediment yields from a disturbed area.

GROSS EROSION AND SEDIMENT YIELD DETERMINATION

When evaluating sedimentation problems, it is generally necessary to make estimates of long-term and single storm sediment yields. Reservoir survey studies and measurements of the suspended sediment load of rivers are the most common method of determining sediment yields in the field. Information from these studies have provided the data base for the development of numerous regional empirical predictive methods.

Long term estimates

In the USA, sediment surveys have been conducted by state and federal agencies for 50 years and the US Department of Agriculture (1973) lists reservoir sediment survey data from over 1500 locations. Commonly used empirical reservoir trap efficiency relationships such as those developed by Brune (1953) and Churchill (1948) are based on sediment survey data.

Rooseboom (1978) studied sediment discharge patterns in South African rivers. Based on an analysis of his sediment survey data, he developed a silt map which shows maximum average annual sediment production rates for different regions in South Africa. Methods for using these maps and for predicting sediment accumulations in South African reservoirs are described in detail by Middleton et al. (1981).

Stocking & Elwell (1973) have developed erosion hazard maps for Zimbabwe. A hazard rating is determined based on rainfall intensity, cover, landslope, soil erodibility and human occupation. The higher the rating, the greater the soil erosion. Hazard ratings can readily be converted into sediment yields if actual sediment production is known at a few locations in the country.

In a study of five large Zimbabwe catchments, Ward (1980) developed a reservoir siltation procedure for Zimbabwe. Ward's results are based on field surveys and can be used to provide estimates of sediment discharges to a reservoir and the sediment trap efficiency of the reservoir. It should be noted, however, that the trap efficiency relationship is based on Brune's USA procedure and that observed measurements at the two reported Zimbabwe reservoirs were much lower than the predicted values.

Single storm events

In the design of sediment control structures it is generally necessary
to estimate sediment yields associated with single storm events as well as long term estimates. Considerable focus has therefore been placed on the development of predictive methods and on the physics of sedimentation. Sedimentation problems occur due to the detachment, transportation and deposition of soil particles. Soil is detached by raindrop impact and the shearing force of flowing water. Sediment is transported downslope by raindrop splash and by water flow (generally surface runoff). The quantity and size of the transported material increases with the velocity of the flows. Downslope or downstream reductions in velocity produce a reduction in the transport capacity of the flow and sediment deposition.

The most commonly used method for predicting erosion is the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1960):

\[ A = R K L S C P \]  

where \( A \) = the soil loss per unit area; \( R \) = a rainfall factor (usually expressed as the product of rainfall energy, times the maximum 30 minute intensity for a given storm); \( K \) = a soil erodibility factor; \( L S \) = a dimensionless length slope factor; \( C \) = a dimensionless soil cover factor; \( P \) = a dimensionless conservation practice factor.

Equation (1) can only be used to determine gross erosion from an area and Wischmeier & Smith (1978) have stated that the USLE may be applied wherever its factor values are known. In southern Africa \( K, K_S, C \) and \( P \) factors are generally determined using information contained in US publications. Methods for determining the rainfall erosivity factor, \( R \), in southern Africa have been developed by Smithen & Schultze (1982).

Elwell (1978) has developed a model for predicting annual soil losses from arable lands on the Zimbabwe highveld. The model is similar in concept to the USLE and is described by the equation:

\[ Z = K C X \]

where \( Z \) = predicted mean annual soil loss (t ha\(^{-1}\)); \( K \) = mean annual soil loss (t ha\(^{-1}\)) from a standard plot 30 m x 10 m at a 4.5% slope for a soil of known erodibility \( F \) under a weed-free bare fallow surface; \( F \) = soil erodibility factor; \( C \) = the ratio of soil loss from a cropped plot to that lost from bare fallow land; \( X \) = the ratio of soil lost from a plot of length \( L \) and slope percent \( S \), to that lost from a standard plot. Determination of the parameters in equation (2) is outlined by Elwell (1978).

To determine the sediment yield at a downstream point, the gross erosion needs to be multiplied by a sediment delivery ratio term (sediment yield/gross erosion). Numerous empirical delivery ratio concepts have been developed and the more commonly used procedures are those of Boyce (1975), Renfro (1975) and the US Forest Service (1980). Unfortunately, very little work has been done in developing delivery ratios for southern Africa and because of the empirical nature of these methods, overseas relationships should be applied with extreme caution in rural African basins.

A method known as the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) overcomes some of the problems of determining a delivery ratio and has seen widespread application. The method is
defined by the equation:

\[ Y = 11.8(Q q)^{0.56} K \text{ LS C P} \]  

(3)

where \( Y \) = single storm sediment yield (t); \( Q \) = storm runoff (m\(^3\)); \( q \) = peak storm discharge (m\(^3\)s\(^{-1}\)); and \( K \), \( LS \), \( C \) and \( P \) are the standard USLE terms used in equation (1).

Although equation (3) accounts for the delivery process on a basin, it should not be used to route the sediment yield from the basin through streams to a downstream point. Williams (1975) has developed a simple procedure to route sediment from a small catchment to a point of interest. The procedure is described by the following equation:

\[ Y_s = Y e^{-BT\sqrt{D_{50}}} \]  

(4)

where \( Y_s \) = downstream sediment yield (t); \( Y \) = upstream basin yield (t); \( B \) = routing coefficient; \( T \) = travel time from a basin to the point of interest (h); \( D_{50} \) = median particle diameter of sediment (mm). Equations (3) and (4) can be used in conjunction with each other to determine the downstream sediment yield at the outlet of a number of small sub-basins.

In addition to the more commonly used procedures which have been discussed, many other methods have been developed for determining gross erosion. A good review of sedimentation procedures is presented by Wilson et al. (1983).

THE SEDIMOT-II COMPUTER MODEL

Overview

The SEDIMOT-II (SEdimentology by Distributed MOdel Treatment) model was developed by the Agricultural Engineering Department at the University of Kentucky (Wilson et al., 1981; Wilson et al., 1983). The model is a single event distributed parameter model which simulates the runoff, erosion and transport process on a disturbed basin. Although primarily developed for application on surface mined basins, the program lends itself well to use on any rural basin.

The program is capable of predicting a hydrograph and sediment-graph for individual sub-basins. These flows are then routed to and through sediment control structures to evaluate the sediment trap efficiency of the controls. A discussion of the hydrological, sediment yield and sediment control modules of the program follows.

Hydrological component

The rainfall-runoff process is modelled using SCS techniques (Soil Conservation Service, 1972).

The rainfall depth associated with a design storm event is converted into a temporal storm pattern by selection of the SCS type 1 or type 2 24 h synthetic rainfall pattern or by inputting a user-developed pattern. Rainfall patterns ranging in duration from 1 to
Sediment yield and sediment control structures

24 h are determined using the technique described by Ward et al. (1979).

Unit hydrograph procedures are used to convert rainfall excess (runoff) into a storm hydrograph. Double triangle hydrograph shapes which correspond to forested, agricultural and disturbed (urbanization, mining or bare soils) land use are provided. This procedure is based on methods developed by Overton & Crosby (1979). Storm hydrographs are routed to structures and between structures by the Muskingum routing procedure (Koussis, 1978).

Sediment yield and sediment transport component

Two procedures have been incorporated into the model for determining sediment yields and for routing these yields from a sub-basin. The first procedure uses the MUSLE (equation (3)) to determine sediment yields and equation (4) to route these yields. The second procedure is based on detachment and transport capacity concepts. Detachment in interrill and rill areas is estimated by procedures which are incorporated in the CREAMS model (Knisel, 1980). The sediment transport capacity of a stream is calculated from Yang’s unit stream power equation (Yang & Stall, 1976). Complete details of how these procedures are incorporated in the SEDIMOT-II model are presented by Wilson et al. (1983).

The model translates sediment yields into sedimentgraphs by assuming that the sediment concentration is proportional to the runoff volume. The basis for this approach is presented in a paper by Ward et al. (1981).

Sediment control options

The model is capable of evaluating the sediment control performance of check dams, sediment dams and vegetative filters. The sediment trap efficiency of a check dam depends upon the relationship between the size distribution of the incoming sediment load and the void spaces in the structure. A check dam is designed to retard the flow and provide quiescent settling conditions. The effectiveness of a check dam is evaluated based upon the backwater surface profile and the particle fall velocity (Hirsche, 1981; Barfield et al., 1981). The procedure requires knowledge of:

(a) incoming sediment size distribution,
(b) design flow characteristics,
(c) check dam porosity,
(d) channel slope,
(e) Manning's n,
(f) channel geometry.

The performance of a sediment pond is determined based on a modification of the DEPOSITS model (Ward et al., 1979). Basic inputs to the model are:

(a) stage-area curve for the impoundment,
(b) stage-discharge curve for the spillway system,
(c) withdrawal characteristics of the spillway system,
(d) particle-size distribution and specific gravity of the sediment load,
(e) sediment load or inflow sedimentgraph,
(f) degree of dead storage (storage volume that is not exchanged),
(g) degree of short-circuiting (by-passing of previously stored flow).

The model uses plug flow concepts to determine the sediment trapped in an impoundment. The inflow hydrograph and sedimentgraph is divided into plugs of flow and each plug is routed sequentially through the impoundment. For each plug of flow, a detention time and average depth of flow is determined and sediment concentrations computed for four layers within each plug. Settling between layers is calculated based on Stokes' law. The model can account for dead storage and short-circuiting and can also be used to simulate bed load deposition.

As an alternative to the DEPOSITS model approach, an impoundment can be considered to operate as a series of continuous stirred tank reactors (CSTRS). The theory of this approach is discussed by Ward et al. (1977), Tapp et al. (1981) and in the user manual for the model (Wilson et al., 1983).

The performance of vegetative filters is simulated based on algorithms developed by Hayes et al. (1979). As sediment-laden flow impinges on a vegetative filter, a reduction in its velocity causes the transport capacity to be lowered, which then results in sediment deposition. Sediment trap efficiency is based on the Reynolds number, particle settling velocities, flow velocity, depth of flow, and the filter length.

Basic inputs are:
(a) filter length, slope and width,
(b) vegetation spacing,
(c) Manning's n,
(d) rigidity factor,
(e) vegetation height,
(f) infiltration rate.

Outputs from each of the three sediment control options (check dams, sediment ponds and vegetative filters) are:
(a) outflow hydrograph,
(b) outflow sedimentgraph,
(c) outflow particle size distribution,
(d) control trap efficiency.

Model verification

Verification studies have been conducted, by the developers of SEDIMOT-II, on the hydrological, sediment pond and vegetative filter components of the model. The accuracy of the hydrological component was evaluated using published rainfall-runoff data for eight different basins with a total of 27 storms. The basins were selected so that each of the different unit hydrograph shape options could be evaluated. The results of this study are presented by Wilson et al. (1981). It was concluded that the observed runoff hydrographs were adequately predicted by the model for a known curve number and temporal rainfall pattern.

Ward et al. (1979) and Tapp et al. (1981) describe several studies that were conducted to evaluate the DEPOSITS model. In general, it was found that the trap efficiency of a pond is adequately predicted by the model. Wilson et al. (1983) present a comparison between the
Sediment yield and sediment control structures

DEPOSITS model and the CSTRS model using the data of Tapp et al. (1981). It was found that the CSTRS was slightly better at predicting effluent sediment graphs but that both models gave good similar predictions of peak sediment concentrations and trap efficiency. The vegetative filter component was tested on the observed data of Hayes et al. (1979) and was found to adequately predict effluent concentrations (Wilson et al., 1983).

Work is currently being conducted at the University of Kentucky on the erosion and deposition process. However, the procedures incorporated into the model were taken directly from the literature and verification studies have already been conducted by the developers of these techniques (Williams, 1975, 1978; Knisel, 1980).

SEDIMENT PREVENTION AND CONTROL

A discussion of sediment prevention and control practices is presented in the following section. Application and the benefits associated with using the SEDIMOT-II model are identified, where appropriate.

An evaluation of sedimentation problems will usually address one or more of the following aspects:
(a) development of preventive measures,
(b) design of control measures,
(c) impact assessments,
(d) design of remedial measures.

The SEDIMOT-II model can be used in making assessments of each of these aspects. Where an evaluation is to be made of a single control structure or of a simple homogeneous basin, it is generally more efficient to apply the techniques contained in the model rather than the model itself. It should be noted that SEDIMOT-II is a simulation model and is only capable of assessing the performance of a series of control measures. The initial designs need to be developed by the model user.

Preventive measures

The major causes of erosion problems in rural areas are poor management, inadequate drainage and the lack of a sediment control strategy. Preventive measures are far more effective than control and treatment measures and will generally be more cost effective for the land owner. Soil conservation should be a major concern of any farmer and should be treated with equal importance to crop production.

Preventive measures which are well suited to application in rural areas are:
(a) drainage control,
(b) terracing,
(c) tillage practices,
(d) mulching.

The effects of these different soil conservation practices can be estimated individually through application of equation (3). Drainage control and terracing will reduce the peak discharges and the volume of runoff from an area. Terracing will also cause a reduction in the LS factor. Tillage practices and mulching will result in
reductions in the CP factor.

For simple situations, equation (3) can be used in conjunction with a storm runoff model such as the WASHMO model (Ward & Stern, 1983). If the SEDIMOT-II model is used, conceptual designs should be developed on an individual basis and a drainage and sediment control plan developed for the area under consideration. This basic plan should then be evaluated by the model. Alternative strategies should be considered and a final plan selected, based on agricultural productivity, soil conservation benefits and economic constraints. Control measures should be considered if preventive measures alone do not keep soil losses within acceptable levels.

Sediment control measures

The main benefit of control measures is that they prevent or reduce downstream pollution and that they contain the transported soils close to the soil. For the farmer, the short-term goal usually is to prevent contamination of the water supply and losses in storage in water storage reservoirs. The most effective measures for this purpose are check dams and sediment ponds upstream of the storage facilities.

To contain agricultural soils close to the source, consideration should be given to placing vegetative filters (buffer zones) down-stream of croplands and fields. If the land is used for grazing, careful management should be adopted and, where practical, a narrow buffer zone left on the downstream side of the grazed areas. Efforts should be made to prevent overgrazing as this practice produces the following adverse impacts:

(a) denuding of the area,
(b) loss of rich organic soils,
(c) soil compaction,
(d) increased runoff and decreased infiltration,
(e) decreased water holding capacity,
(f) a loss in fertility,
(g) gully erosion during severe storms.

Single ponds can be designed using hand calculator procedures or the DEPOSITS model. Individual vegetative filters can be designed by using the procedures presented by Barfield et al. (1981).

Impact assessments

Complex basin models, such as the SEDIMOT-II model, are best suited for application in the making of impact assessments. It is often difficult or undesirable in regional studies to evaluate the impacts of proposed developments on a piecemeal basis and a model such as SEDIMOT-II should be used. Rural applications of this nature might include proposed:

(a) irrigation schemes,
(b) agricultural development,
(c) silviculture,
(d) mining,
(e) industrial or urban development,
(f) construction of weirs, dams or reservoirs,
(g) upstream impacts on existing hydraulic structures.
Remedial measures

Remedial measures which are most commonly required in rural areas include:

(a) weir and impoundment desilting,
(b) gully reclamation,
(c) dirt road maintenance.

Removal of sediment from hydraulic structures is a difficult and costly exercise. If cleanout is necessary, it is generally advisable to conduct a study to evaluate the probable frequency of future cleanouts and to evaluate the feasibility of modifying inlets and outlets to promote self desilting.

In the USA, considerable work has been conducted on the desilting of agricultural impoundments (Rausch & Heinemann, 1975). Some of the information collected during these investigations was used in the verification studies with the DEPOSITS model. It was found that the model gave good estimates of the actual performance of a desilting syphon at the outlet of a reservoir.

Extensive work has been conducted in South Africa on gully reclamation works (Crosby et al., 1977). Basic techniques which have been adopted are weirs and a series of reed beds upstream of the weirs. The dual performance of these two procedures is readily modelled as the reed beds act as vegetative filters and the weir acts as an instream silt trap.

CONCLUSION

Only a brief overview of erosion and sediment yield procedures has been presented as an introduction to the SEDIMOT-II model. The information presented is not intended to be comprehensive and does not consider wind erosion.

Sufficient information about SEDIMOT-II has been presented to inform the agricultural engineer of the technical basis of the model, the validity of the model and applications of the model. Space constraints have precluded inclusion of detailed examples of the model application. It is felt, however, that some of the techniques incorporated in the model are well suited to application on small farms but that, in general, the model is better suited as a planning aid in regional studies or as a design tool where severe erosion is a problem.

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