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Soil Erosion Study of Exposed Highway Construction Slopes and Roadways

BRADLEY A. ANDERSON AND DARYL B. SIMONS

The quantities of sediment produced from construction slopes and roadways are determined, and a methodology to assist in the determination of these quantities is presented. During the study a portable rainulator was fabricated and applied to collect water runoff and soil erosion data from forest logging roads in northern California. The data collection program was conducted on 10 representative soils in the study area and included testing of cut slopes, fill slopes, road surfaces, and undisturbed sites above the roadway. The data were analyzed and used as input to a simple mathematical model. Additional input parameters were estimated and the model was calibrated. The mathematical model was found to reproduce accurately measured values of water and sediment yield from the roadways. After the mathematical model was calibrated, a procedural guide and an interactive program were developed. Both can be used to assist the forest planner in determining the sediment produced from different roadway geometries and in assessing roadway design alternatives.

Erosion resulting from the construction and use of highways is a problem that continues to plague highway planners and designers. The sediment generated during and after construction is often excessive unless proper erosion control measures are taken. These measures, which should be incorporated in every roadway design, vary in nature from vegetative to structural methods for controlling erosion. In selecting the optimum roadway design, it is necessary to estimate the erosion that will be generated as a result of the design. Hence, methods or procedures for determining these erosion quantities are essential to the selection process.

A recent study conducted by Colorado State University for Region 5 of the U.S. Forest Service (1) culminated in the development of two methods for estimating water and sediment yield from roadways of different designs. The study included (a) selection of a mathematical model to simulate the erosion processes, (b) a field data collection program to provide input to the mathematical model, (c) refinement of the mathematical model based on the collected data, and (d) generation of a procedural guide and an interactive program. The procedural guide provides the field practitioner with a simple and useful method of estimating water and sediment yields for use in road design and environmental impact analysis. The interactive program provides the same capability but eliminates the time-consuming hand calculations required by the procedural guide.

MODEL SELECTION, COMPONENTS, AND DATA INPUT

Predicting water and sediment yields that result from highway construction and use is a complex problem. Solutions to this problem depend on the accurate estimation of a wide array of variables and usually require the use of a mathematically based model. Regression models based on limited field data are unable to cope with this problem on a widespread basis because (a) they are restricted by the data from which they are developed, (b) they assume that the physical environment is both time- and space-invariant, and (c) they tend to group controlling processes into a few coefficients. This grouping decreases the usefulness of the model in examining the effects of individual processes on water and sediment yield from the road.

Physical process models, on the other hand, represent the system being modeled by decomposing it into its respective components, thus avoiding the lumping of processes or parameters. By simulating selected phenomena through separate components, each process can be individually analyzed and refined or altered to meet the needs of the user. As each process component is upgraded, the model becomes more representative of the physical system. The use of component process models also allows the input of variables that have physical significance to the user and the field situation. In addition, because these models are formulated according to physical processes, they are applicable to areas where the governing natural phenomena are the same. Consequently, physical process models are becoming more widely used in assessing ecosystem responses. In some cases, however, such models are as complex and difficult to understand and to use as the process system they simulate.

The limitations of regression models and the user restrictions imposed by more complex physical process models led to the development of simplified physical process models. Model simplification can reduce complexity and, if the simplification maintains the basic physical processes, there will be no significant loss in accuracy. This is the basis for the simplified physical process model selected for this study.

The simplified model was developed by Simons, Li, and Ward (2) to aid in assessing sediment yield from sites subject to erosion. It most readily conformed to the requirements of the study and was selected for its widespread applicability to roadways and construction sites. The physical processes considered in the simplified model include interception losses, infiltration, determination of water yield, and determination of sediment yield by comparing sediment transport capacity with sediment supply. The determination of the sediment supplied during a storm involves consideration of erosion by raindrop splash and overland flow.

Application of the simplified physical process model required a knowledge of key input data, including geometry, soil characteristics, vegetative data, overland flow resistance parameters, size distribution of sediment, and rainfall data. Most input data were available through the field data collection program, and other input parameters were estimated by using established guidelines (3).

FIELD DATA COLLECTION PROGRAM

Before the mathematical model could be used to estimate soil loss and rainfall runoff from specific locations, an on-site field data collection program was required. Critical to the field data collection program was the generation of specific rainfall conditions created by a portable rainfall simulation system (rainulator). Once fabricated, the rainulator could be used to collect the data needed to analyze rainfall and sediment variables associated with roadway erosion.

The data collection program was conducted during two consecutive field seasons and included the testing of two typical roadway designs (in-slope and out-slope). The out-slope roadway design normally consisted of cut slope, road surface, and fill slope (see Figure 1). The in-slope roadway design included a ditch between the cut slope and the road surface (see Figure 2). On two separate occasions, the watershed area above the cut slope was also tested. In some of the soils tested, the slumping of cut slope materials into the ditch provided a constant source of sediment for transport by ditch runoff. Although the contribution of sediment from the ditch was not separately measured or evaluated, it was taken into consideration and measured as part of the sediment contributed from the cut slope.

Reliable measurement of the water and sediment discharge from the field plots was important to the success of the study. Parshall, HS, and cutthroat flumes were considered for measuring water discharge. Important considerations included accurate low-flow measurement, easy field installation, and durability. After field tests were conducted, HS flumes were selected and mounted with mechanical water-level recorders to measure water runoff. Sediment yield was measured by taking grab samples of the flume discharge at 2-min intervals. The grab samples were later analyzed to determine sediment concentration.

Preparing a site for data collection involved defining the boundaries of the test area, performing a location survey to establish the geometric characteristics of the test area, and then installing the rainulator system and the measuring flumes. The boundaries of the test area were defined with berms and isolation and drainage trenches. Isolation trenches and berms were used to prevent the runoff from the areas adjacent to the site from entering the test area. Drainage trenches were used to collect the runoff occurring within the test area. Whenever possible, the rainulator system was positioned to allow simultaneous testing of three of the four subsites (watershed, cut slope, road surface, and fill slope) with trenches defining the boundaries.

Wind conditions were the primary criteria used to determine whether or not a test run would be conducted. A steady wind of more than 5 to 7 mph or the occurrence of wind gusts would disrupt the uniform rainfall distribution over the test area. If the wind conditions were favorable, samples were taken before the test run. These samples included topsoil swept with a whisk broom from three 2x2-ft areas within each subsite and soil cores for moisture measurements taken just before the test run. The topsoil samples were used to determine the material available for transport by the runoff. Moisture samples taken from three areas within each subsite were used to evaluate antecedent moisture conditions. Drainage trenches were flushed with water to the point of saturation before a run to minimize infiltration losses in the trench. This also removed loose soil and organic material from the trenches. A soil binder was also used to prevent additional

Figure 1. Out-slope road design.

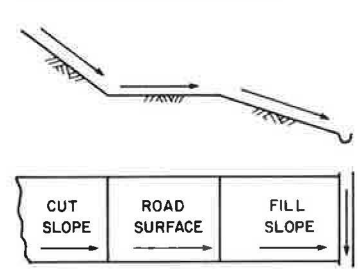
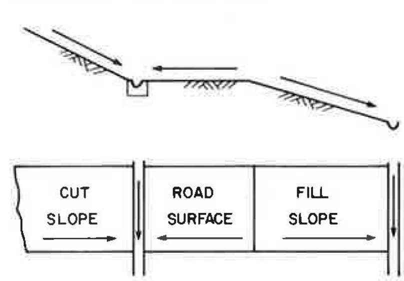


Figure 2. In-slope road design.



erosion from occurring due to the channelization of runoff within the trench system.

When sufficient water was available for a 20-min test run and all prerun samples were obtained, the test run began and the data were collected. Discharge samples were taken at 2-min intervals in accordance with the procedure previously described. After the rainfall ended, bottles were sealed and labeled, charts were collected, topsoil and moisture samples were taken, and rain gage readings were tabulated. A detailed discussion of the field data collection program, including analysis of the collected data and the tabulated results, is provided in the report by Simons, Li, and Anderson (1).

RESULTS

The analysis of the collected data provided the input needed to apply the simplified mathematical model. Application of the model indicated whether the collected data were physically realistic and whether the measured results could be reproduced. Information on specific input parameters was obtained by analyzing the data base and was then used for model calibration.

The results of the model application are shown in Figures 3 to 6. Figures 3 and 4 show the correlation of the predicted and measured water yields for the two consecutive field seasons. The correlation of the predicted and measured sediment yields is shown in Figures 5 and 6. Good agreement is shown in Figures 3 and 4 because rainfall and runoff were used to verify the soil infiltration parameters. Figures 5 and 6 for sediment yield show that small yields are more difficult to reproduce because of the larger relative magnitude of measurement errors and the inherent variability in the mechanics of erosion. These results do indicate, however, that road sediment yields can be modeled by using rainulator data and that the model realistically reproduces the measured values.

APPLICATIONS

After it was verified that the mathematical model could reproduce the measured values, it became the primary tool in producing a quantitative procedural guide and an interactive program capable of estimating soil loss and runoff volumes from timber access

Figure 3. Measured versus predicted water yield: first field season.

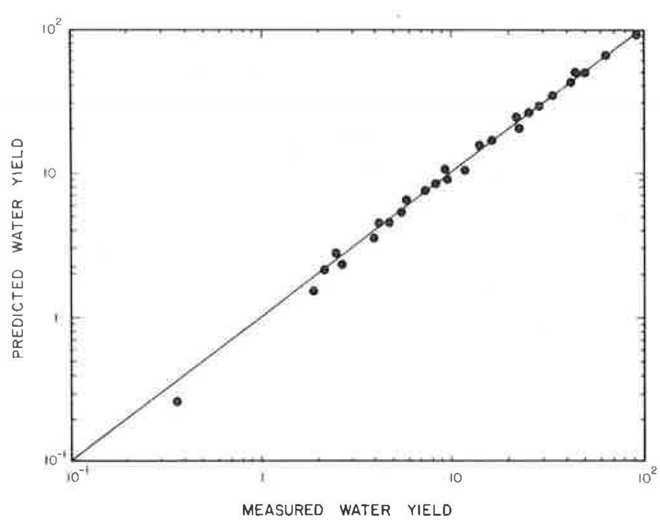


Figure 4. Measured versus predicted water yield: second field season.

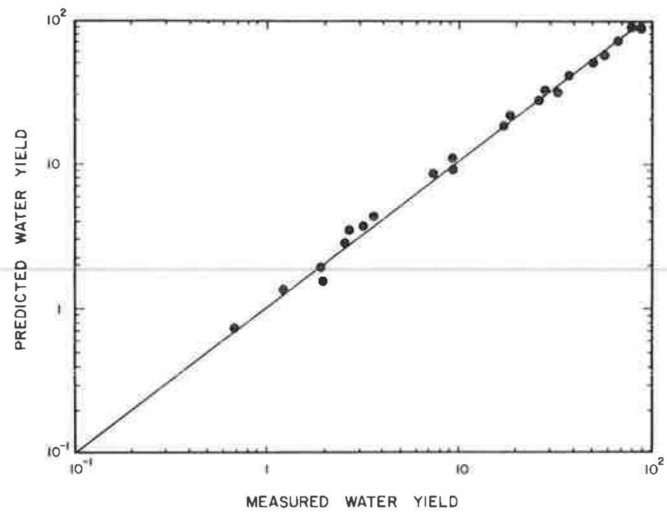


Figure 5. Measured versus predicted sediment yield: first field season.

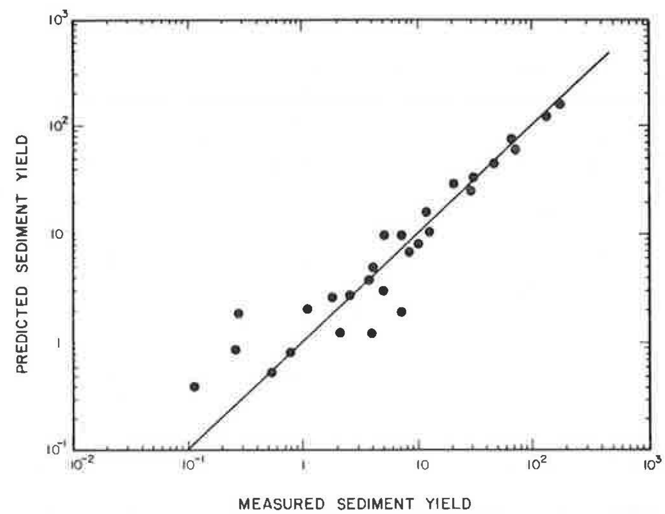
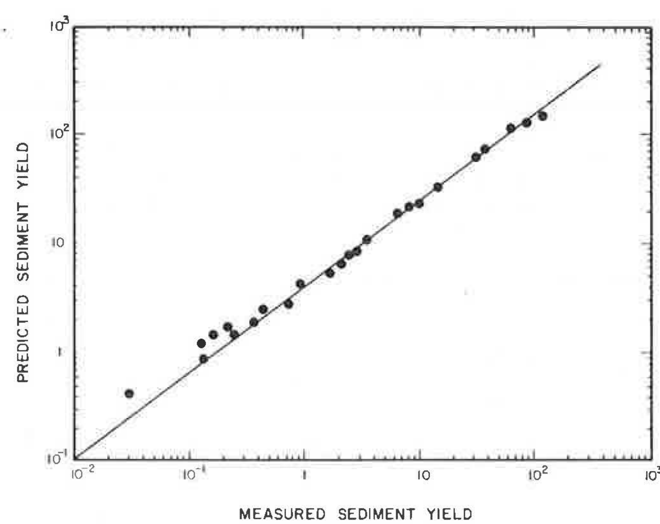


Figure 6. Measured versus predicted sediment yield: second field season.



roads. Both products are able to assess the effects of changing input conditions and land use practices and can subsequently assist in the selection of the optimum roadway design alternative.

In producing the procedural guide and the interactive program, a correction for the difference in the erosion index (EI) between a simulated rainstorm and a natural rainstorm was applied. The average value of the EI for the portable rainulator system was determined to be 40 percent of that for natural rainfall. Research has indicated a directly proportional relationship between the EI and soil loss (4,5). Further research indicated that when simulated rainfall EI values are made equal to natural rainfall EI values by an approximate straight-line adjustment, soil loss values measured under simulated rainfall can be adjusted accordingly (6). In the procedural guide, the adjustment to account for the difference in the values for the EI was made to the sediment supplied by raindrop splash because this quantity is directly related to the magnitude of the EI. By using the reciprocal of 40 percent, all values obtained for material detached by raindrop splash are increased by a factor of 2.5.

Procedural Guide

The procedural guide generated by the mathematical model consists of series of design graphs and has been documented in a separate report by Simons, Li, and Anderson (7). The graphs relate such variables as rainfall intensity, storm duration, infiltration rate, sediment size, ground cover conditions, road gradient, inclination of cut and fill slopes, and water and sediment discharge. As an aid to the forest planner, the procedural guide provides an effective means of determining the sediment discharge from various roadway design alternatives and is especially suited for use by field practitioners.

The governing factors considered in the procedural guide were determined by a sensitivity analysis that involved use of the road sediment model and consultation with personnel from U.S. Forest Service Region 5. The factors considered are rainfall intensity, storm duration, ponding time for surface water, infiltration rate, soil detachment rate, sediment size, ground cover conditions, road gradient, inclination of cut and fill slopes, and sediment and water discharge. The ranges of the key design factors considered in the procedural guide are given in Table 1.

Changing ground cover conditions included gravel pavement on the roads and sparse and dense grass or vegetation on the cut or fill slope. Also incorporated in the development of the procedural guide were 10 representative soil types from Region 5: cobble-stony clay loam, Dubakella gravelly loam, Boomer gravelly loam, Nuens very gravelly loam, Nuens-Sheetiron very gravelly loam, Cagwin loamy sand, Chaix sandy loam, Windy sandy loam, Josephine gravelly loam, and Musick loam.

The series of graphs generated for the procedural guide includes graphs for determining ponding time, rainfall excess rates, and potential sediment transport capacity. Figures such as Figure 7 were generated, showing the ponding time from which surface runoff begins on each cut, road, and fill section for each of the 10 soils. Additional figures, such as Figure 8, provided rainfall excess rates resulting from different rainfall intensities and storm durations of 15, 30, and 60 min. Together, Figures 7 and 8 can be used to make a quick estimate of the volume of rainfall excess and the corresponding water yields. The complete procedural guide includes six figures for determining ponding time and 18 figures for determining rainfall excess rates.

Figures for determining the overall sediment transport capacity were generated next. The figures developed encompassed eight sediment sizes; varied cut, road, and fill slopes; bare soil and gravel pavement as the road surface; and dense and sparse vegetation on the cut and fill slopes. Figure 9 shows an example of the generated relationship between sediment transport capacity and water discharge for a bare soil road surface and a sediment size of 0.10 mm. For the bare soil road surface, 8 figures encompassing the eight sediment sizes were developed. A total of 64 figures were generated to aid in determining the overall sediment transport capacity for a variety of cut, road, and fill slope conditions.

Table 1. Range of key design factors in the procedural guide.

Design Factor	Value
Roadbed gradient	0.01 to 0.20
Slopes (horizontal to vertical)	
Cut	0.5:1 to 2:1
Fill	1:1 to 3:1
Rainfall intensity (in./hr)	1 to 16
Sediment size for determination of transport rate (mm)	
Clay and silt	0.01
Very fine sand	0.1
Fine sand	0.2
Medium sand	0.35
Coarse sand	0.75
Very coarse sand	1.5
Very fine gravel	2.8
Fine gravel	5.5

Figure 7. Ponding time versus rainfall intensity for road surface.

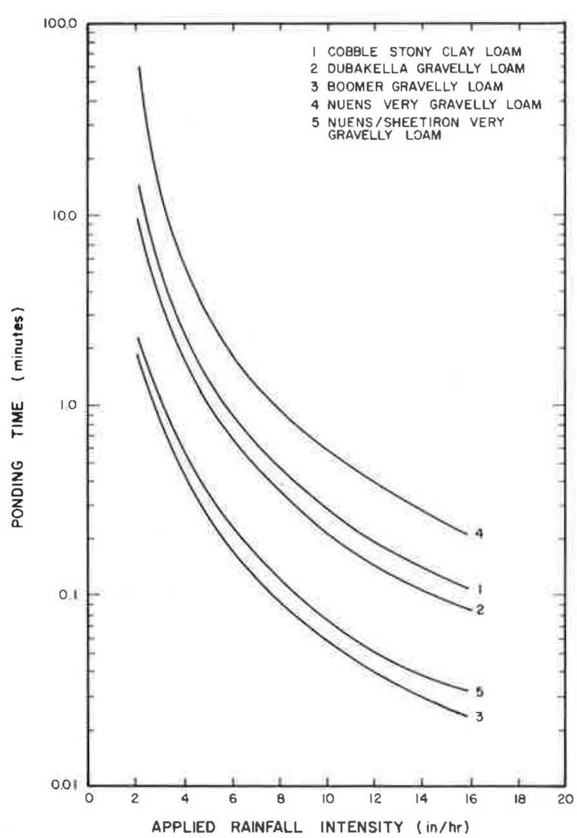


Figure 8. Rainfall excess rate versus rainfall intensity for storm duration of 30 min for road surface.

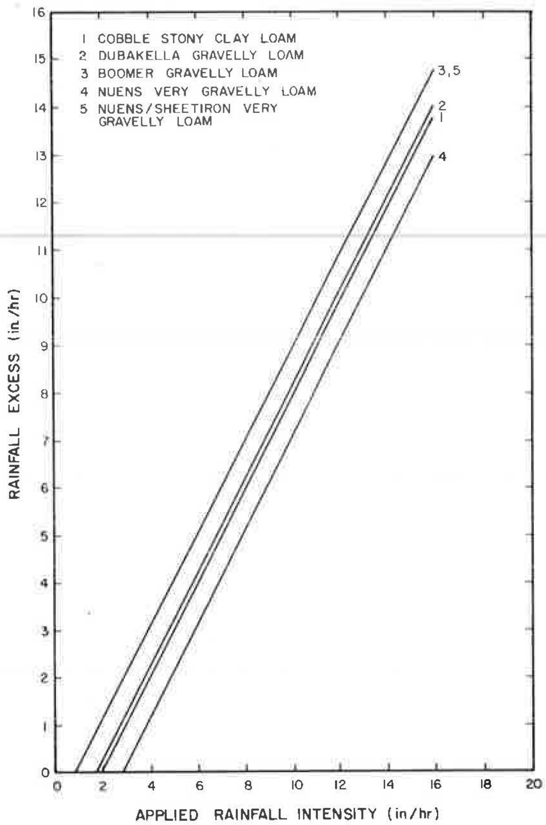
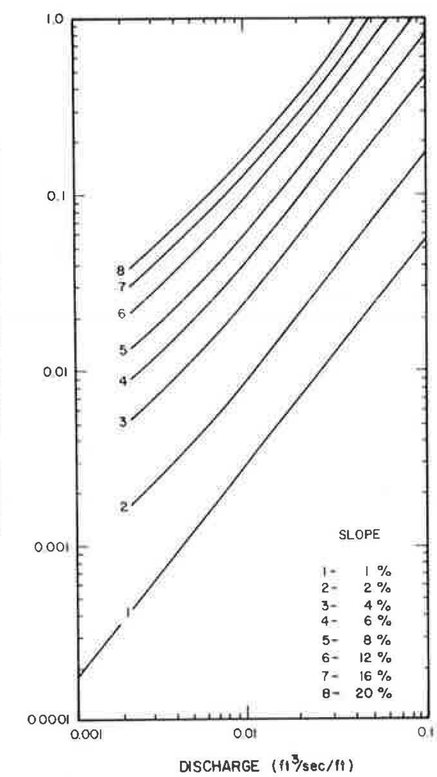


Figure 9. Sediment transport capacity versus water discharge for bare soil road surface and sediment size of 0.10 mm.



With the aid of the figures, the total potential sediment transport capacity can be determined. The sediment yield can then be approximated by comparing the total sediment transport capacity and the overall sediment availability or supply during the storm.

The supply comes from two mechanisms: detachment by raindrop splash and detachment by overland flow. Detachment by raindrop splash can be formulated as a simple power function of rainfall intensity (8):

$$\bar{V}_r = a_1\, i^2\, LWT\,(1 - \phi)\, A_b \tag{1}$$

where

$\bar{V}_r$ = nonporous volume of material detached by raindrop splash,
i = rainfall intensity,
T = storm duration,
a_1 = empirically determined constant describing erodibility of the soil,
A = area reduction factor,
ϕ = soil porosity,
L = length, and
W = width.

The variable A_b represents the fraction of unprotected or bare soil in the area and is given as

$$A_b = 1 - C_g - C_c + (C_g C_c) \tag{2}$$

where

C_g = ground cover,
C_c = canopy cover, and
$C_g C_c$ = areas of cover overlap.

As mentioned previously, the raindrop splash detachment volume for natural rainfall must be adjusted by a factor of 2.5 to allow for the difference in EI values exhibited by simulated and natural rainfall. With this factor, the volume of material detached by raindrop splash for natural rainfall becomes

$$\bar{V}_r = \bar{V}_r \times 2.5 \tag{3}$$

Sediment supply by overland flow detachment is determined by

$$\bar{V}_f = D_f\,(\bar{V}_t - \bar{V}_r) \tag{4}$$

where

$\bar{V}_f$ = volume of soil detached by overland flow,
D_f = flow detachment coefficient, and
$\bar{V}_t$ = volume of potential transport determined from the generated figures.

If $\bar{V}_t < \bar{V}_r$, there is no overland flow detachment because the transport rate is limited by the transport capacity and $\bar{V}_f$ is equal to zero. The total available sediment supply is

$$\bar{V}_a = \bar{V}_r + \bar{V}_f \tag{5}$$

Sediment yield is controlled by either supply or capacity. If supply is greater than capacity, capacity controls, and vice versa. As particle size changes, so do capacity and supply. Therefore, supply and capacity must be compared for each particle size. The individual capacity is determined by

$$\bar{V}_{t_i} = \bar{V}_t\, P_i \tag{6}$$

where

P_i = percentage of each sediment size,
$\forall_{t_i}$ = individual demand or capacity for the particle size, and
$\forall_t$ = total transport capacity determined from the figures.

The available supply is

$$\forall_{a_i} = \forall_a P_i \quad (7)$$

where $\forall_{a_i}$ is the available supply for the particle size. Values of $\forall_{a_i}$ and $\forall_{t_i}$ can now be compared. If $\forall_{t_i}$ is greater than $\forall_{a_i}$, supply controls; if $\forall_{a_i}$ is greater than $\forall_{t_i}$, capacity controls; or

$$\forall_{y_i} = \forall_{a_i} \quad \text{if } \forall_{t_i} > \forall_{a_i} \quad (8)$$

and

$$\forall_{y_i} = \forall_{t_i} \quad \text{if } \forall_{t_i} < \forall_{a_i} \quad (9)$$

where $\forall_{y_i}$ is the volume yield for the particle size fraction. The total yield will then be

$$Y_s = \gamma_s \sum_{i=1}^{N} \forall_{y_i} \quad (10)$$

where Y_s is the sediment yield by weight.

The procedures for using the procedural guide and estimating water and sediment yields are illustrated in nine example problems presented by Simons, Li, and Anderson (7). Each example provides a detailed step-by-step procedure for determining water and sediment yield. In the interest of brevity, an example is not included in this paper.

Interactive Road Sediment Program

The interactive road sediment program resulted from a reformulation of the mathematical model. It is capable of producing the same results as the procedural guide and has the added advantage of executing all time-consuming calculations and procedures quickly and efficiently. The interactive computer program has the obvious limitation of computer accessibility and requires that the user have a basic understanding of interactive computer operating procedures.

The data input for the interactive program was derived directly from the data base used by the calibrated model. One set of data exists for each of the 10 soils tested in the study. It is a special feature and an obvious advantage of the interactive program that the user can quickly edit each data set to allow for changes in slope, geometry, number of rainstorms, rainfall intensity and duration, soil suction pressure, hydraulic conductivity, saturation index, porosity, ground cover, canopy cover, and canopy and ground cover interception values. As in the procedural guide, this feature provides the flexibility needed to model the water and sediment yields from similar soils in the study area while considering changes in roadway design, location, maintenance, and various stabilization and treatment measures. The input values entered interactively by the user to change the data sets should be determined after a thorough investigation of the site to be modeled. In some instances this may require an on-site inspection for an estimation of ground and canopy cover and the collection of soil samples needed to determine the appropriate infiltration parameters.

The interactive program provides as output a listing of the pertinent input parameters, estimated water yield, estimated sediment yield by size fractions, and total sediment yield. Output is generated and displayed for each storm and surface type. A report by Li, Collette, and Anderson (9) documents the use and editing procedure of the interactive program. It also provides examples of application, listings of input and output data, an explanation of the computer language used, and the amount of storage required. The example that follows illustrates program execution, input prompts, and output generation.

Determine the water and sediment yield from a road surface given the following information: length = 500 ft, width = 10 ft, slope = 0.04, ground cover = 0.05, storm intensity = 3 in./hr, storm duration = 1 hr, and soil = Boomer gravelly loam. (The data input values contained in the data base will be edited in this example.) After the appropriate execution command has been issued, the terminal responds with the following.

```
    SELECT THE SOIL TYPE THAT BEST CORRESPONDS TO THE
    SOIL BEING EVALUATED.
         0 :  STOP
         1 :  COBBLE STONY CLAY LOAM
         2 :  DUBAKELLA GRAVELLY LOAM
         3 :  BOOMER GRAVELLY LOAM
         4 :  NUENS VERY GRAVELLY LOAM
         5 :  NUENS/SHEETIRON VERY GRAVELLY LOAM
         6 :  CAGWIN LOAMY SAND
         7 :  CHAIX SANDY LOAM
         8 :  WINDY SANDY LOAM
         9 :  JOSEPHINE GRAVELLY LOAM
        10 :  MUSICK LOAM

    ENTER CORRESPONDING NUMBER FOR SELECTION
?   3
    SELECT SURFACE DESIRED
         0 :  NO SLOPE DESIRED
         1 :  CUT
         2 :  ROAD
         3 :  FILL

    ENTER CORRESPONDING NUMBER FOR SELECTION
?   2

    DO YOU WISH TO EDIT THE ROAD DATA?
    ENTER YES OR NO
?   YES

    DO YOU WISH TO EDIT THE GEOMETRY DATA FOR THE
    SELECTED SURFACE?

    SLOPE LENGTH (FEET)                 31.00
    WIDTH         (FEET)                41.39
    SLOPE   (DECIMAL FRACTION)            .13

    ENTER YES OR NO
?   YES
    ENTER SLOPE LENGTH (FT)
?   500
    ENTER WIDTH (FT)
?   10
    ENTER SLOPE (DECIMAL FRACTION)
?   .04

    DO YOU WISH TO EDIT THE RAIN DATA FOR THE
    SELECTED SURFACE?

    NUMBER OF RAIN STORMS =             1
    STORM       DURATION            INTENSITY
                (HOURS)             (INCHES/HOUR)
    1.          .33                 2.53

    ENTER YES OR NO
?   YES
```

```
    ENTER NUMBER OF RAIN STORMS
?   1

    DO YOU WISH TO EDIT THE RAINFALL DURATIONS?
    ENTER YES OR NO
?   YES
    ENTER RAINFALL DURATION (HRS) FOR STORM  1
?   1

    DO YOU WISH TO EDIT RAINFALL INTENSITIES?
    ENTER YES OR NO
?   YES
    ENTER RAINFALL INTENSITY (IN/HR) FOR STORM  1
?   3

    DO YOU WISH TO EDIT THE SOIL DATA FOR THE
    SELECTED SURFACE?

    SOIL SUCTION HEAD             (INCHES)          .480
    HYDRAULIC CONDUCTIVITY (INCHES/HOUR)            .600
    SATURATION INDEX   (DECIMAL FRACTION)           .300
    POROSITY           (DECIMAL FRACTION)           .450

    ENTER YES OR NO
?   NO

    DO YOU WISH TO EDIT VEGETATION DATA FOR THE
    SELECTED SURFACE?

    GROUND COVER (DECIMAL FRACTION)                  .10
    CANOPY COVER (DECIMAL FRACTION)                 0.00
    GROUND COVER INTERCEPTION (INCHES)               .50
    CANOPY COVER INTERCEPTION (INCHES)              0.00

    ENTER YES OR NO
?   NO

    ==================================================

    SOIL TYPE       :  BOOMER GRAVELLY LOAM
    SOIL SURFACE    :  ROAD

              SOIL PARAMETERS

    SOIL SUCTION HEAD (INCHES)                  .48
    HYDRAULIC CONDUCTIVITY (INCHES/HOUR)        .60
    SPECIFY GRAVITY                            2.65
    SATURATION INDEX (DECIMAL FRACTION)         .30
    POROSITY (DECIMAL FRACTION)                 .45

              VEGETATION PARAMETERS

    GROUND COVER (DECIMAL FRACTION)             .10
    CANOPY COVER (DECIMAL FRACTION)            0.00
    GROUND COVER INTERCEPTION (INCHES)          .05
    CANOPY COVER INTERCEPTION (INCHES)         0.00

              GEOMETRY PARAMETERS

    SLOPE LENGTH (FEET)              500.0
    SLOPE WIDTH   (FEET)              10.0
    SLOPE                                .04

              SOIL SIZE DISTRIBUTION

    GRAIN SIZE (MM)                  PERCENT BY WEIGHT
       15.41                                .22
        4.36                                .58
        1.41                                .09
         .71                                .05
         .35                                .01
         .18                                .01
         .10                                .01
         .06                               0.00
         .01                                .03

              WATER YIELD

    STORM                                       1
    DURATION OF RAINFALL (HOURS)             1.00
    RAINFALL INTENSITY (INCHES/HOUR)         3.00
    TIME TO PONDING (HOURS)                   .01
    RUNOFF VOLUME (CUBIC FEET)             878.44

              SEDIMENT YIELD

    GRAIN SIZE (MM)            SEDIMENT YIELD (POUNDS)
       15.41                        0.00
        4.36                        0.00
        1.41                        0.00
         .71                        7.41
         .35                        5.10
         .18                        7.67
         .10                        7.67
         .06                        0.00
         .01                       23.02

    TOTAL SEDIMENT YIELD (POUNDS) :  50.87
```

SUMMARY AND CONCLUSIONS

The results and methods derived from this study represent significant steps toward the accurate and simplified estimation of water and sediment yields from roadways. The simplifications have been incorporated to enable the relatively untrained individual to estimate these erosion quantities. The two major accomplishments of this study, the procedural guide and the interactive program, have been documented and represent advancements in these areas. This is not to say that other methods of estimating the sediment generated by roadways have not been developed. On the contrary, previous studies have documented procedural guides similar in scope and methodology to the one discussed here. However, they have only been applied qualitatively and have exclusively considered soils consisting of a single sediment size.

The procedural guide produced as a result of this study considers 10 different soils composed of a wide range of sediment sizes. Furthermore, it has been derived from the results of a field data collection program and can be applied quantitatively to estimate the sediment generated by various roadway design alternatives. Even though increasing the number of size fractions makes the computations more tedious and time-consuming for the individual user, the capability of the procedural guide to estimate the sediment yield from complex soils enhances its versatility and applicability and is considered a worthwhile trade-off.

A number of computer programs and mathematical models for determining the sediment yield from roadways have also been developed and are available. They often require a basic knowledge of the modeling processes as well as of the physical significance of the input parameters. The model used in this study is an example of such a model. The data base assembled during this study, however, was incorporated as an integral part of the interactive program, and this factor, coupled with the interactive capability of the program, has eliminated this requirement. Thus, the interactive program is ideally suited for the untrained user to produce results with only a limited knowledge of interactive computer operating procedure. In addition, the interactive capability of the program permits rapid appraisal of changes in road gradients, cross sections, route locations, types of surfacing, and spacing of cross drains in relation to the quantities of sediment produced.

However, the limitations as well as the capabilities of the procedural guide and the interactive program must be recognized and addressed. Both methods are limited regionally to the soils tested and the sites evaluated during the study. Furthermore, the interactive program and the procedural guide are limited to assessing the erosion from relatively simple road geometries. In spite of these limitations, however, it is conceivable that, with an expanded field data collection program, improved methodologies similar to those presented in this paper could be produced for any selected geographic region.

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Roadside Erosion Causes and Factors: Minnesota Survey Analysis

ROXANNE SULLIVAN AND LAWRENCE E. FOOTE

A roadside erosion survey was conducted along all state, county, and township roads in Minnesota. The locations and estimated volumes of roadside erosion, cross-sectional road designs, roadway ownership, type and causes of erosion, and history of the road (time since construction disturbance) were noted. The total estimated soil loss was 116,203,336 ft^3 at 17,902 sites located along 115,570 miles of roadway. The cross-sectional design that resulted in the most soil loss was the cut-fill design. The fill design had the lowest soil-loss volume. Erosion occurred most often along at-grade roads and least often along fill roads. Volumes and occurrences were slightly more along township than along county roads and much less along state roads. Ditch bottoms were the most common location of erosion on roadsides and water-related erosion was the major type. Although erosion occurred more often along older roads, eroded sites were larger along newer roads. The larger sites were generally caused by (a) inadequate design in areas with rough terrain or poor soils or near waterways and (b) lack of administrative direction and emphasis on establishment of cover and control of unauthorized activities, including farming the right-of-way and use of roadsides as borrow areas or for recreation. Erosion was often associated with drainage from adjacent areas, steep slopes, inadequate design, and lack of administrative direction and emphasis. Corrective measures were recommended, and many counties fully implemented such measures. However, some sites remain uncorrected and others have increased. Lack of funds is the main reason for the absence of corrective measures, particularly on township roads. More construction of roads with a fill cross-sectional design and less of cut-fill roads, especially in rough terrain, should reduce the potential for future erosion.

The potential for erosion is ever present. The process of detachment, transportation, and redeposit of sediment is by far the greatest contributor of pollution to streams and lakes. Sediment in waterways increases turbidity, inhibits photosynthesis, interferes with respiration of aquatic organisms, tends to destroy habitat, and degrades water quality. Sedimentation in culverts, ditches, stream channels, reservoirs, and other conveyance or storage structures decreases capacity and reduces the effectiveness of such structures. The removal of sediment from these structures and public water supplies is costly. Loss of topsoil by erosion reduces vegetation productivity and increases rainfall runoff.