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P.O. Box 2841
Littleton, Colorado 80161, U.S.A.

REPRINTED FROM THE BOOK:

MODELING COMPONENTS OF HYDROLOGIC CYCLE

A PART OF THE
Proceedings of the International Symposium on Rainfall-Runoff Modeling held May 18-21, 1981 at Mississippi State University, Mississippi State, Mississippi, U.S.A.

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EXPERIENCE WITH A PROCESS-ORIENTED ROAD SEDIMENT MODEL

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ABSTRACT

Simulated rainfall events were applied to selected sections of mine haul roads to generate surface runoff and sediment for testing of ROSED (Road Sediment Model). ROSED is a process-oriented runoff and erosion prediction model developed at Colorado State University. Parameter needs for ROSED determined the format for collection of field data.

A definite improvement in sediment prediction accuracy was obtained by modifying model input to simulate wheel ruts, where applicable, in addition to the side ditch. Total runoff volume could be predicted within ±20 percent for 75 percent of the rainfall events, and runoff peak flow within ±10 percent for 67 percent of these events. Total sediment yield could be predicted within ±25 percent for 62 percent of the rainfall events.

Recommendations for improved field techniques for road erosion studies include: additional rain gages outside the plot boundary for more accurate rainfall distribution maps; and multiple event marker equipment to record beginning and ending of rainfall and runoff, rainfall intensity, and dye travel time all on a common time base.

Recommendations for future investigations with ROSED include: simulation of more complex runoff surfaces, such as wheel ruts; adjustment of model parameters for simulated snowmelt and rainfall with low kinetic energy; relationship of hydraulic roughness parameters to site characteristics; and the relationship of infiltration parameters to easily measured site characteristics.

INTRODUCTION

Impacts on water resources by road construction, operation, and maintenance are identified as concentrated surface runoff, soil disturbance and loss, disruption of surface and groundwater flow patterns, and degradation of water quality. Effects of these impacts on land use, water supplies, wildlife, and fisheries are generally considered detrimental. Environmental laws now dictate that these impacts and effects be estimated at the planning stage of road projects. Effective, workable tools are needed to quantify these impacts for forest roads and surface mine haul roads.

In 1975, as a cooperative effort between USDA Forest Service and Montana State University, evaluation began on ROSED (Road Sediment Model), a tool to estimate runoff and sediment yield from roads. We felt that ROSED had the best potential as an operable tool to meet the assessment needs. It is a process-oriented runoff and erosion prediction model developed by Simons, Li, and Shiao (1977) at Colorado State University. In the model testing, we used simulated rainfall applied to selected sections of surface mine haul roads to generate runoff and sediment yield data. Simulated rainfall was used for two reasons: (1) natural precipitation during the field season is infrequent and of short duration over much of the Northern Great Plains coal region; (2) instrumentation of a number of road sections to await natural precipitation is expensive and risks loss of data through instrument malfunction. Therefore, a modified Colorado State University rainfall simulator (rainulator) was used to generate rainfall on isolated sections of road. This report details the rainulator tests, summarizes the data, and gives an evaluation of the ROSED model. We also offer suggestions for improved field techniques for rainulator studies and recommendations for future studies and modifications to the ROSED model.

OVERVIEW OF THE RAINFALL SIMULATOR STUDY

Field procedures for rainulator operation and data collection were guided primarily by data needs for the ROSED model and by the state-of-the-art for studies using simulated rainfall (USDA-SEA, 1979). A review of ROSED documentation (Simons, Li, and Shiao, 1977; Simons, Li, and Ward, 1977; Simons et al, 1979) and our observation of road surface erosion indicated three major areas of uncertainty in the relationships between model parameters and site characteristics: (1) the interaction of loose soil stored on the road surface and the runoff detachment coefficient in the prediction model; (2) the interaction among model flow resistance parameters, the particle size gradation of road surface material, and hydraulic roughness of the surface; and (3) estimation of infiltration of water into the road surface using measurable site characteristics. Supplementary data of various types were collected to help eliminate these uncertainties in addition to the usual field procedure for rainulator studies.

The modified CSU rainulator consists of a set of sprinkler heads on 11-ft (3.35 m) risers with sprinkler pressure controlled by a regulator at the base of each riser. This rainulator calibration by Neff (1979) showed: (1) uniform areal distribution for plots up to 3,000 ft^2 (279 m^2) at wind speeds less than 7 mi/hr (11.3 km/hr) and decreasing uniformly thereafter; (2) drop size less than natural rainfall of the same intensity; (3) kinetic energy about 40 percent of natural rainfall events.

Support equipment included a 5,000-gal (18.93 m^3) water storage bag, a 250-gal/min (0.95 m^3/min) pump, and a 2,000-gal (7.57 m^3) tank truck. Measurement equipment included a triangular, supercritical Replogel flume, a FW-1 stage recorder with 120-volt electric chart drive, recording rain gage, nonrecording rain cans, nuclear density measurement instrument, a hot-wire anemometer, and water sample bottles.

FIELD PROCEDURE

Road sections for application of simulated rainfall were selected for uniformity of surface configuration, road gradient, and surface materials. Each road section was considered a unique plot and no attempt was made to replicate plot conditions. Test sections were selected with a wide variety of length, width, and slope characteristics within the normal standards for mine road design and construction.

Sections with a ditch-to-ditch width of 34 ft (10.4 m) or less could be covered entirely by the rainulator system. Maximum effective coverage of 4,420 ft^2 (0.1015 acre or 410.6 m^2) could be attained by using 24 sprinklers in 3 parallel rows 17 ft (5.2 m) apart, each with 8 sprinklers at 20 ft (6.1 m) spacings. Adjacent rows were shifted 10 ft (3.05 m) to create a staggered effect for more uniform coverage. Half widths of wider roads were used by having the mining company grade a berm along the road crown, then setting the rainulator over the berm-to-ditch width. Figure 1 shows a typical rainulator layout.

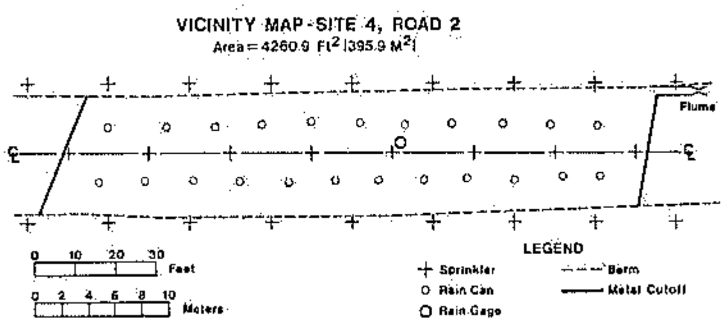

Figure 1--Sample vicinity map for a rainfall simulator plot on a surface mine haul road.

Each selected road section was isolated by excavating a shallow ditch and installing metal cutoff walls across the upper and lower ends of the section. Side borders were provided by the earth berms normally constructed on the sides of mine roads in compliance with safety regulations. A chemical soil stabilizer was sprayed on the ditch-berm perimeter to prevent extraneous sediment contribution from these areas. A metal trough was placed to collect and convey water from the lowest corner of the road section to the flume.

The recording rain gage and supplementary rain cans were located in a grid upon the road section to measure rainfall distribution. Soil was scraped from the first centimeter of the road surface at random locations to accumulate a 5- to 10-lb (2.3 to 4.6 kg) composite sample. In addition, loose soil on the road surface was measured by sweeping and collecting the soil from within a 4-ft^2 (0.37 m^2) area enclosed by a metal ring 2.26 ft (0.69 m) in diameter. These samples were taken before and after rainfall application at several random locations across the section. Bulk density measurements were made (nuclear equipment) and soil moisture samples were collected before and after each rainfall application.

Reference pins 10 ft (3.05 m) apart and alined in the expected direction of overland flow were placed at various locations on the road section. The velocity of overland flow at these locations was measured periodically during rainfall application by placing a small mass of dye upslope from each 10-ft spacing and timing the passage of the center of mass between the pins. The time of each test was recorded so that these dye travel measurements could be related to the runoff hydrograph.

Water was applied at a uniform rate of approximately 2 in/hr (5.1 cm/hr) for at least 30 minutes, usually during the early morning when the air was relatively calm. Tests were suspended when wind gusts exceeded 5 mi/hr (8.05 km/hr). Field data included the times of beginning of detention storage, overland flow, entry of runoff into the flume, and times when rainfall began and rainfall and runoff stopped. At the flume outlet, 0.26-gal (1 liter) samples were collected at 1-min intervals during the rising stage and at 2-min intervals from the peak runoff through the recession limb of the hydrograph.

Rainfall was applied until runoff stabilized or until the water supply was exhausted. After rainfall stopped, the catch in the rain cans was measured and compared with the rain gage record to evaluate uniformity of coverage. If a second run with the road in a prewetted condition was desired, then the procedure was repeated the following day or during the same day if wind conditions allowed. After all runs on a road section were completed, a tape and level survey was made to map the location to the nearest 0.1 ft (3 cm) and elevation to the nearest 0.01 ft (0.3 cm) of plot boundaries, sprinklers, rain gage, and rain cans (see fig. 1).

A motion picture camera, set for a time lapse mode, photographed each plot during simulated rainfall. These films provided graphic evidence of the timing of runoff from portions of the plot and provided clues to accurate modeling of response units and the routing sequence.

REDUCTION OF FIELD DATA

All soil samples were placed in sealed containers and shipped to the Civil Engineering Department laboratories at Montana State University in Bozeman. Each sample was weighed and dried, then a particle size gradation curve was developed using American Society for Testing Materials procedures with wet and dry sieving and hydrometer analysis. Soils analysis also included determination of Plasticity Index and Liquid Limit and measurement of particle density by means of an air pycnometer.

Water samples were filtered with Millipore equipment to determine sediment concentrations (gm/cc). Sediment from each run was saved and particle size gradation curves were developed to characterize the sediment yield at intervals during the runoff hydrograph.

We used three methods to measure rainfall distribution over each road section: arithmetic mean of the rain-can catch; Thiessen polygons; and isohyets drawn with computer graphics. The arithmetic mean gave reliable results for these data with considerable savings of time. The recording rain gage record was used to distribute the total catch over 1-min intervals for the length of the simulated rainfall.

The large amount of data generated by these rainfall simulator tests required a heavy reliance on computer digitizing of rainfall data, observed hydrographs, and measured sediment yield. Several data management programs were written to expedite data analysis. Special computer graphics programs were developed (Pexton, 1979) for direct display and comparison of observed hydrographs and sedimentgraphs with predictions. These programs greatly improved our ability to rapidly evaluate the quality of field data and the accuracy of ROSED results.

Observed runoff hydrographs were digitized and each file of stage readings was converted to a file of average stage for a preselected time interval (0.5 min). This file was then linked to a program with the Replogle flume rating equation to produce a file of runoff rates (ft^3/min), runoff volume in area-inches/min, and cumulative runoff volume in ft^3. Files of sediment concentration (lb/ft^3) were multiplied by runoff rates (ft^3/min) to develop a file of sediment discharge (lb/min) for graphical display and comparison with predicted sedimentgraphs.

ANALYSIS OF FIELD DATA

The ROSED time-space water and sediment routing procedure uses a conceptual road prism with five response units: cut slope, fill slope, road surface, ditch, and culvert. Three types of flow are considered: overland flow, ditch flow, and culvert flow. In this study, we considered only road surfaces and ditches that involve only overland flow and ditch flow. The ROSED model used in this study produces two distinct but interconnected outputs: (1) a hydrograph by estimating rainfall excess, overland flow routing, and ditch flow routing; and (2) a sedimentgraph by estimating soil detachment by rainfall, soil detachment by overland flow, overland flow sediment routing, soil detachment by ditch flow, and ditch flow sediment routing. All these processes of detachment, transport, and storage are modeled by incremental time units.

Our approach in this study has been to estimate ROSED model parameters from an operational standpoint using simple measurements of site characteristics whenever possible. A standardized procedure has been developed to use rainfall simulator data as a result of close communication with ROSED developers to prevent misinterpretation of model parameters. This section will only dwell on those model parameters of particular importance in this study.

The most critical step in setting up ROSED is to define the relationship of each response unit to the water and sediment routing sequence. Very simple combinations of response units and routing sequences were used in a preliminary trial with data from each road with mixed results--some good and some poor simulations. Time lapse photographs of runoff from road sections showed how water actually flowed over the surface and emphasized the importance of even minor wheel ruts in overland flow routing. Subsequent modeling runs were more successful because realistic road configurations were used taking wheel ruts into account.

The road sections fell into two groups: (1) those in which runoff moved transversely from the road crown to a lateral ditch, down the lateral to the cutoff ditch, and from there to the flume; and (2) those in which runoff moved transversely to ruts in the road surface, then longitudinally down the ruts to the cutoff ditch and from there to the flume. In case 1, there are two relatively short sections of overland flow into two relatively long side ditches; in case 2, several relatively short sections of overland flow empty into several long central ditches (wheel ruts). Figure 2 shows the configuration for case 1 for both half road widths and full widths as compared to case 2. Dimensions of overland flow length, slope gradient, ditch length and gradient, and ditch side slope were taken from contour maps made for each road section from survey data.

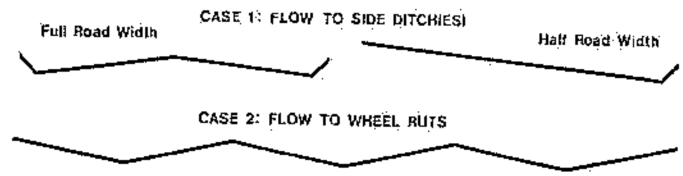

Figure 2--Model configurations used with ROSED in analysis of surface mine haul road data.

Soil detachment by raindrop impact can be a significant factor in surface erosion. However, the rainfall simulator used in this study produces only about 40 percent of the kinetic energy of a natural 2-in/h (5.08 cm/h) rainstorm. For this reason, in this study soil detachment from the road surface by simulated raindrops is considered to be negligible and model parameters related to this process were adjusted accordingly.

A value for overland flow resistance for use in these tests was determined by consulting with ROSED developers. Because there is no method to use site data to determine the value of this coefficient, we selected a tabular value from the documentation (Simons et al, 1979) and used this constant value on all analyses reported here.

Preliminary tests with dye travel data indicate that the overland flow resistance parameter may vary from -20 percent to +25 percent away from the constant value used in this study. We are continuing analyses designed to determine if the overland flow resistance parameter may be estimated from measurements of surface soil particle size gradation data and other site characteristics.

The runoff detachment coefficient must be determined for each overland flow and ditch segment. An empirical procedure to calculate this parameter was suggested by Simons et al (1979):

$$Df = \frac{K(D_{50})^2}{0.63} \qquad (1)$$

where: Df = soil detachment coefficient for runoff
K = soil erodibility index from the Universal Soil Loss Equation (Wischmeier et al, 1971)
D_{50} = median soil particle size in millimeters

The ROSED procedure for calculating infiltration is based upon the Green-Ampt equation and requires estimating saturated hydraulic conductivity. Field measurements of bulk density and laboratory measurements of particle density were used to estimate void ratio and porosity. Field measurements of soil moisture were converted to percent saturation. For the highly compacted road materials used in this study, there are no readily available procedures for relating hydraulic conductivity to site characteristics in the ROSED documentation provided. In this study, the difference between the rainfall rate and the peak runoff rate is used as an estimate of the saturated hydraulic conductivity for calculations of infiltration. This procedure has the disadvantage that each rainfall simulation is "optimized" by using data from that simulation to calculate the infiltration rate. The result is that the difference between observed and predicted runoff volumes tends to be minimized.

RESULTS

Observed and predicted runoff volumes and sediment yields from selected rainfall simulations are shown in table 1. Note that the error in estimating runoff volume is usually less than the error in estimating sediment yield. One factor in more accurate estimation of runoff volume is found in the discussion in the last section.

We made 24 individual applications of rainfall. Of these, only 13 sets of data were used to evaluate ROSED. The remaining data sets were eliminated because of errors caused by wind effects, lack of rainfall intensity data, and faulty layout of cutoff ditches.

Figure 3A shows the results of a simulated rainfall test and gives the measured rainfall intensity averaged over 1-min intervals together with the observed runoff hydrograph. This shows the results of simulated rainfall on highly compacted road sections with slow infiltration rates. There is very little difference between total rainfall volume

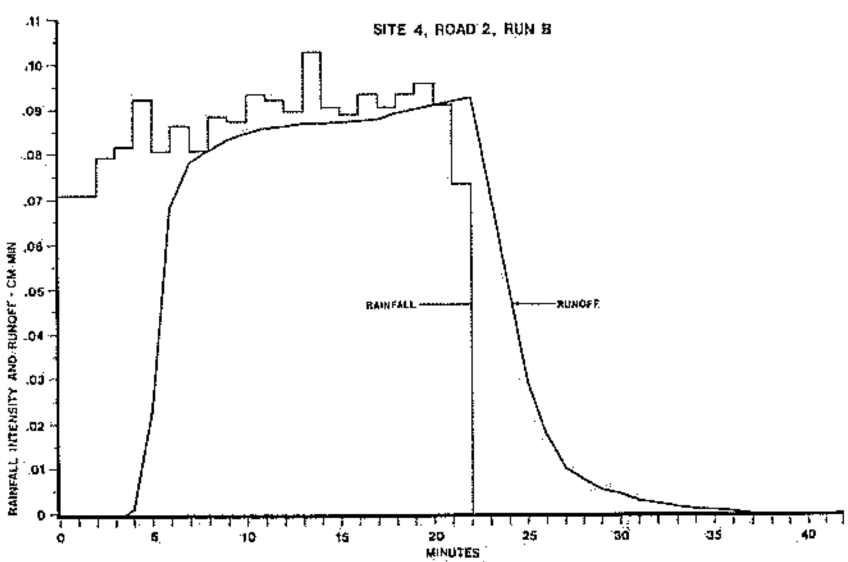

Figure 3A--Comparison of observed runoff and applied rainfall.

Table 1.--Predicted and measured values of runoff and sediment from selected sets of simulated rainfall data

Location	Predicted Runoff (m^3)	Observed Runoff (m^3)	Error (%)= $\frac{P-O}{O} \times 100$	Predicted Sediment (kg)	Measured Sediment (kg)	Error (%)= $\frac{P-O}{O} \times 100$
Site 1, Road 1, Run A	1.01	1.31	-23	13.74	16.96	-19
Site 3, Road 1, Run A	1.96	1.68	+17	41.14	52.03	-21
Site 3, Road 1, Run B	1.51	1.77	-15	31.89	46.31	-31
Site 3, Road 2, Run C	3.34	3.08	+ 8	47.17	37.51	+26
Site 4, Road 1, Run A	1.99	2.10	- 5	37.92	51.07	-26
Site 4, Road 2, Run A	2.06	2.32	-11	38.28	36.29	+ 5
Site 4, Road 2, Run B	6.57	6.43	+ 2	72.12	92.71	-22
Site 5, Road 1, Run B	10.96	11.39	- 4	122.92	89.04	+38
Site 5, Road 3, Run B	7.81	7.09	+10	88.45	80.42	+10

and total runoff volume, and between the rainfall rate and the peak runoff rate. Any error in measuring rainfall intensity can cause a significant error in estimation of saturated hydraulic conductivity according to the procedure used in this study.

Figure 3B illustrates the close estimation of hydrograph shape and peak flow rate that is possible with this model as used in this study. The rising and falling limbs of the predicted hydrographs typically lag behind their corresponding observed hydrographs. We found that the model could estimate total runoff volume with ±20 percent for 75 percent of the simulated rainfall events and estimate peak flow rates within ±10 percent for 67 percent of the events. These errors were considered to be acceptable for our preliminary evaluations of ROSED.

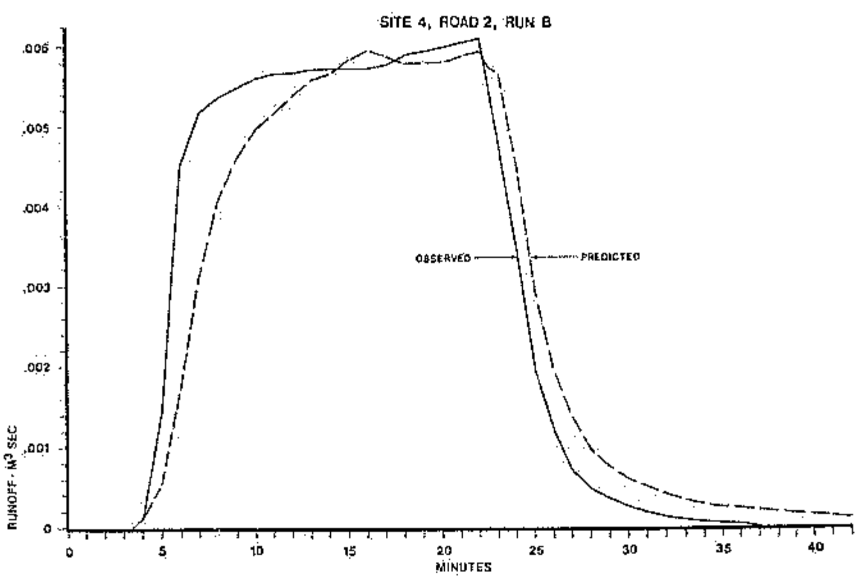

Figure 3B--Comparison of observed runoff with predicted runoff.

Figure 3C shows a typical sedimentgraph estimated by the model. In most cases the general shape of the actual sedimentgraph is matched fairly closely, although the total estimated volume of sediment is usually underestimated. Total predicted sediment yield was within ±25 percent for 62 percent of the 13 rainfall events modeled; this range of errors is also considered acceptable. The estimated sedimentgraph also shows a slower rise and recession than the observed graph. This is probably because the estimated hydrograph also lags.

Wind effects that cause uneven distribution of rainfall and fluctuations in rainfall intensity over the plot, as shown in figure 4A, can also cause erratic prediction of runoff and sediment yield. The model appears to be quite sensitive to changes in rainfall intensity as evidenced by fluctuations in the hydrograph in figure 4B as compared to the observed hydrograph. The fluctuations in the estimated hydrograph cause corresponding fluctuations in the estimated sedimentgraph (fig. 4C) that are not seen in the observed sedimentgraph.

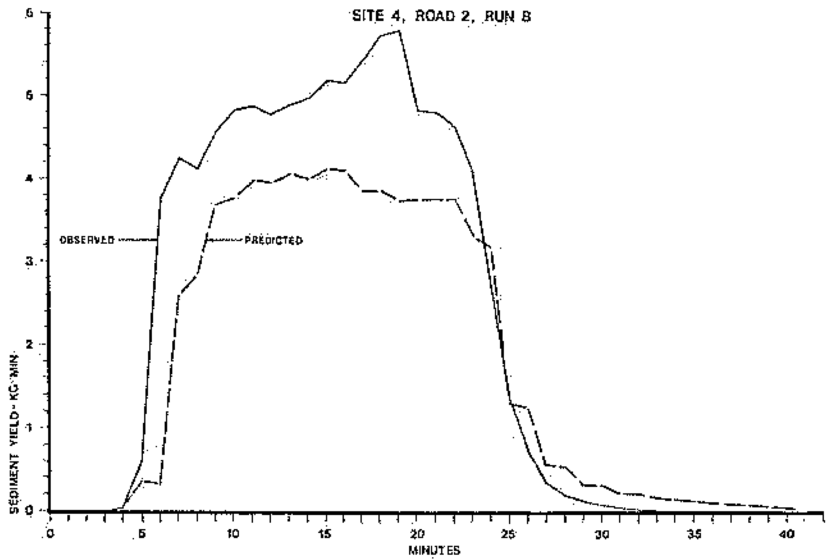

Figure 3C--Comparison of observed sediment yield with predicted sediment yield.

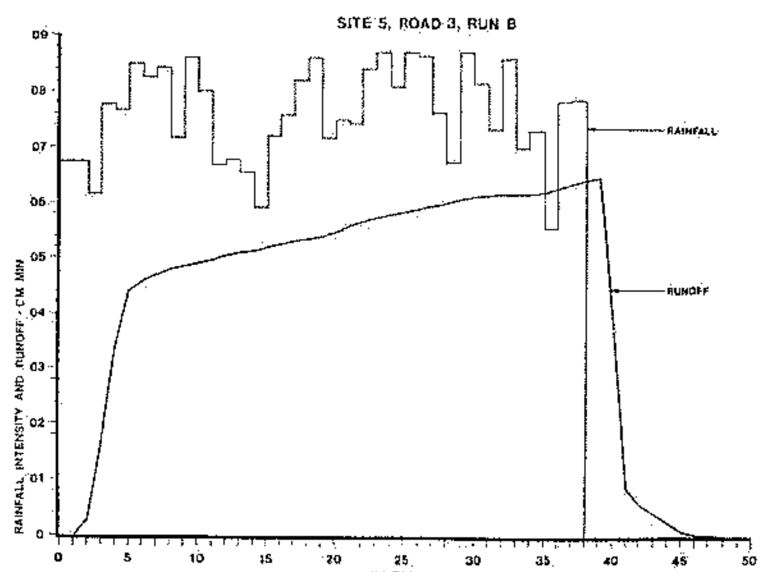

Figure 4A--Comparison of observed runoff and applied rainfall showing wind effects.

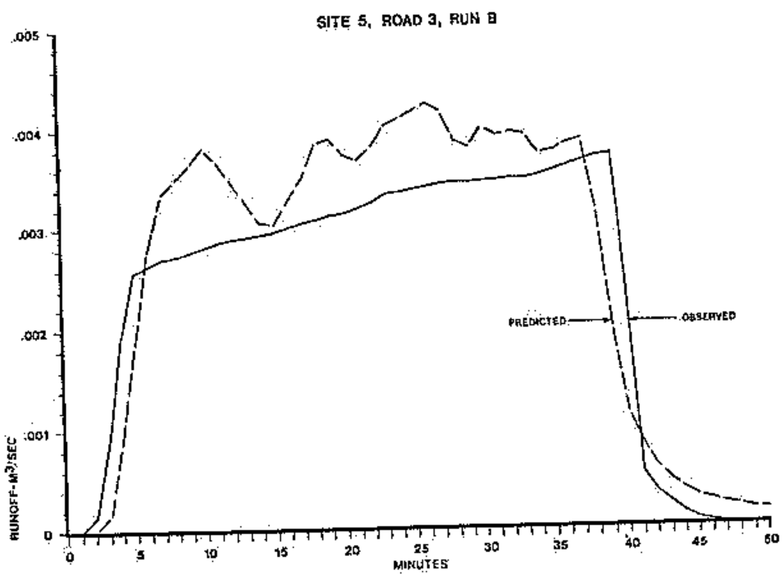

Figure 4B--Comparison of observed runoff with predicted runoff showing wind effects.

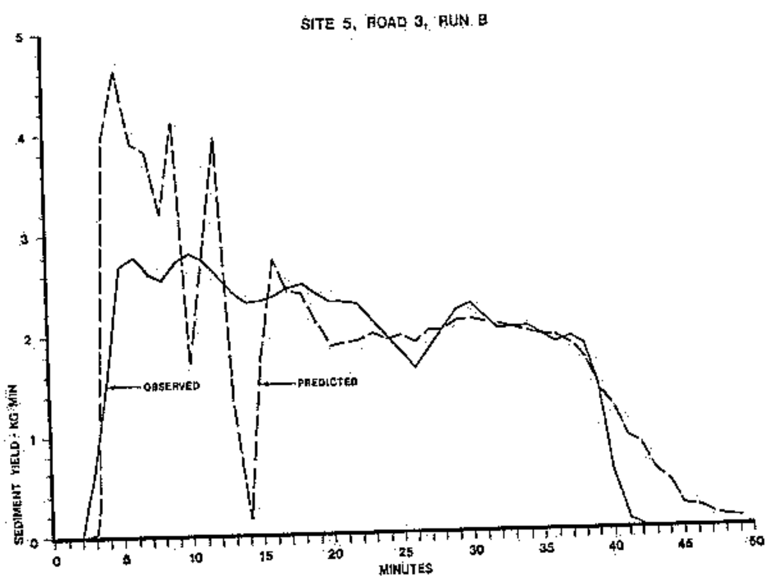

Figure 4C--Comparison of observed sediment yield with predicted sediment yield showing wind effects.

DISCUSSION

Our analysis of these results indicates several sources for the errors between predicted and observed hydrographs and sedimentgraphs. First, heavily compacted road surfaces prevent accurate measurement of bulk density with the nuclear equipment we used. One reason for this is that pounding the spike into the road surface to create a space for the gamma depth probe sometimes cracks the soil and makes neutron readings suspect. Bulk density measurements with surface gamma density meters could not give reliable estimates of changes in subgrade density with depth.

The high density of the surface material also confounds accurate determination of soil moisture contents before and after applied rainfall because of the limited pore space in the soil. Inaccurate measurements of both bulk density and soil moisture content can seriously affect the accuracy of infiltration rate calculations using the procedure in the model.

Our interpretation of the model indicates that while ROSED can be configured to represent wheel ruts, only one side slope can be used for all ditches and wheel ruts. The model also assumes a V-shaped configuration for all ditches and wheel ruts even though trapezoidal or hyperbolic shapes may be found in the field. These constraints limit the flexibility needed to simulate the actual shapes of the road surface, ditches, and wheel ruts.

The importance of the ability to simulate wheel ruts cannot be overemphasized. We observed that wheel ruts can be an extremely important feature in routing water and sediment from the forest road surface.

RECOMMENDATIONS FOR IMPROVED FIELD PROCEDURE

Simulated rainfall offers opportunities for systematic evaluation and testing of runoff and erosion models for use on roads. Our field experience with simulated rainfall indicates several areas where improved field technique would result in better data.

The nonrecording rain gage grid should be extended 3 to 7 ft (1 to 2 m) beyond the plot boundaries in order to improve estimation of the aereal distribution of rainfall. At least two recording tipping bucket rain gages should be randomly located within the plot to provide accurate rainfall intensity data.

A multichannel data recording system is needed so that rainfall records, dye travel times, time to ponding, and so forth, all appear on a single chart with a common time base. This would help speed up data analysis and reduce errors caused by using data from several different types of charts each with its own time scale. Runoff hydrograph charts would continue to be separate, but the stage recorder would use a 1-min tick mark from the multichannel master recorder so that the hydrograph can be related exactly to the common time base.

Techniques are needed for better integrated measurement of soil moisture in the upper 2 inches (5 cm) of the road surface--particularly at near saturation. This would not be a problem for less highly compacted soils. Gravitational samples taken immediately after rainfall ceased did not provide any information on soil moisture at depth. These samples were not related to a known volume so that accurate estimates of percent saturation could be made. Surface soil moisture measurements with neutron scattering equipment were tried and abandoned because they were too time-consuming, and they caused excessive disturbance of the plot surface and compromised the accuracy of succeeding simulator runs.

RECOMMENDATIONS FOR FURTHER MODEL DEVELOPMENT

Our experience with the version of the ROSED model we used indicates it cannot be used as an operational planning tool as it now stands. Our work shows several specific developmental needs that would greatly improve the utility of this model. The engineer or resource specialist concerned with estimating runoff and sediment yield from an existing or planned road has limited specific information to work with: soil particle size gradation, bulk density, road width, length, grade, storm characteristics, and so forth.

Techniques are needed to relate this elementary information to parameters used in the model. Specific model parameters requiring attention are: hydraulic roughness of the road surface, infiltration and hydraulic conductivity, and detachment by raindrops and runoff. Simons, Li, and Shiao (1976) recommended development of handbooks for field use of ROSED "to evaluate alternative routes and alternative designs of road cross sections, road gradients, and surfaces, cut slopes, embankments, and spacings of cross drains."

The addition of a snowmelt component to ROSED would greatly increase the utility of this model in the northern states, especially in mountainous regions. At this time, the mechanics of sediment movement at the soil / snowpack interface is not well understood. Modeling a snowmelt event may only require complete suppression of detachment by raindrops and overland flow in order to emphasize channel flow detachment and transport.

CONCLUSIONS

Our experience with the ROSED model is generally positive. We feel it represents a major step in the development of an operational planning tool to estimate runoff and sediment yield from low standard roads. ROSED has some flexibility to model different road prism configurations, but more is needed to model various ditch shapes and ditch side slopes.

Simulated rainfall allows testing of the ROSED model on road sections with various characteristics of slope, shape, and surfacing. These tests allow the user to determine the sensitivity of model parameters over a range of site characteristics. Further development is needed to relate model parameters to site characteristics so that ROSED may be used by land managers and resource specialists not familiar with the mechanics of this model.

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