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EFFECTS OF HIGHWAY CONSTRUCTION ON SEDIMENT LOADS IN STREAMS

Highway construction is often held responsible for significant increases in suspended sediment yield in adjacent streams. Little factual information has been available to objectively evaluate the validity of this accusation. A study has been conducted to obtain the relationship between highway construction and change in suspended sediment yield in stream systems. A field investigation was carried out in a drainage basin, through which an Interstate highway was being constructed, to collect data necessary for the development of a prediction method. This paper describes an investigation of the effects of rainfall, construction phases, and proximity of construction to the stream system on the quantity of sediment transported. Field data for the analysis were collected at four rain gauge sites, at eight stream stations, and over approximately 5 miles of highway construction. A regression equation relating the observed variables to the sediment yield is presented and discussed. Results indicate that the sediment supply to the streams increases with rain energy, clearing and grubbing, embankment work, and proximity of construction to stream. It is concluded that the results of the study may be employed as a means of predicting whether highway construction would be a significant pollution source for a particular site, a criterion to be considered by an engineer during location studies, and a basis to evaluate the effectiveness of attempts to control sediment yield from construction areas.

Sediment transport and sedimentation resulting from the erosion of soil materials are serious polluters of the aquatic environment. Although the movement of sediment is a natural part of the hydrologic system, highway construction is often considered one of the major sources of sediment in streams. Actually few data are available that can establish the exclusive contribution of an area undergoing highway construction, and a method of predicting this contribution has not been developed.

A general method for predicting sediment yield in a stream system from uncontrolled highway construction could be used in many ways. It could be employed simply to determine whether highway construction would be a significant pollution source at a particular site, and, as such, it could be one of the criteria considered by an engineer during location studies. It would define the variation of sediment yield with the construction process, which would allow necessary abatement works to be phased with the construction rather than requiring completion of controls before construction could begin. Thus construction would not be delayed, and the result would be savings of time and money for the public. The predicted values would be useful as the required capacity in the design of desilting basins or sediment traps. It could also be employed as the basis for comparison to determine the effectiveness of attempts to control sediment yield from highway construction areas.

A tremendous amount of work has been performed in the past 40 years to develop prediction methods for rainfall-erosion soil losses from agricultural areas. The results of much of this work have been combined into the USDA universal soil loss equation (1), which includes as independent variables rainfall, soil erodibility, slope length and gradient, cropping management, and erosion control practice factors. But highway construction usually exposes to rainfall slopes steeper than those found in agricultural applications, which results in greater quantities of runoff at higher velocities. Soils in embankments are placed at near optimum compaction, resulting in lower infiltration rates and greater runoff. Subsoils are exposed that may have erodibility factors different from those of the topsoils studied in agricultural work.

In the past several years, reports (2, 3) have been published that extend the application of the universal soil loss equation to construction areas. The methods require that assumptions be made relative to the cropping management and erosion control practice factors and to the extrapolation of slope length and gradient factor from previous results to the conditions encountered in construction. They incorporate the results of recent research (4) on the soil erodibility factor for subsoils. It should be noted that the result of the application of these methods is the soil loss from a construction area and not the sediment yield in the stream system draining from the area.

Vice, Guy, and Ferguson (5) reported on a study conducted in northern Virginia of suspended sediment transport in a stream that drained an area undergoing extensive highway construction. They related the sediment yield to mean storm flow, duration of storm runoff, area of construction, and a seasonal factor. The rainfall effect was not directly considered in the study, and the intensity and dispersion of the construction, as well as the location of the construction relative to the stream system, were not included.

This paper reports on the development of an equation that may be used for computing the suspended sediment load carried by a stream system during periods of rainfall-induced erosion of disturbed soils common to highway construction. The equation was derived from data collected for a study during the construction of an Interstate highway through a drainage basin in central Pennsylvania during the period 1968 to 1970. The basin is drained by White Deer Creek, which empties into the West Branch of the Susquehanna River approximately 15 miles upstream of its confluence with the North Branch of the Susquehanna River at Sunbury, Pennsylvania.

BASIN CHARACTERISTICS

The White Deer Creek drainage basin extends from the mouth of White Deer Creek at the West Branch of the Susquehanna River, 440 ft above sea level, westward about 26 miles to its source, 1,900 ft above sea level. It has a total drainage area of approximately 46 square miles.

The terrain of the basin is typically a deep synclinal valley, bounded on the north by South White Deer Ridge and on the south by Nittany Mountain. The flanks of the valley are covered with a coarse colluvium, ranging up to boulder size. The stream runs through coarse-graded alluvium in the center of the valley and nearly coincides with the axis of the syncline. Fluvial and detrital deposits cover certain areas of the valley floor, primarily in the western part of the highway project area, and contain a higher percentage of finer constituents than the talus material that covers the mountain slopes.

The underlying bedrock is composed principally of shales of increasingly younger age, from the gray, brown-weathering Clinton shales on the west to the red shales of the Bloomsburg formation on the east, with Tuscarora sandstone on the upper hillsides and crests. These formations are all of Lower Silurian age. Also present are the more deeply underlying Juniata and Bald Eagle formations consisting of sandstone with shale interbeds, both of the Upper Ordovician age.

Topography in the basin is relatively steep, with slopes from ridges to streams averaging about 25 percent. Slopes in the valley from mountain base to stream range up to 10 percent. Stream slopes range from about 1 percent on White Deer Creek to as high as about 7 percent on Mile Run, a tributary of the creek.

The climate in the basin is characterized as continental and inland, with prevailing winds from the west and southwest. Warm summers and moderately long winters are typical of the area. The valley has a freezing depth of approximately 30 in. The mean annual temperature is 50.2 F with a winter mean of 27.9 F and a summer mean of 71.0 F. The average frost-free season is 161 days, although frost may occur as late as May 29 and as early as September 3. The mean annual precipitation is 41.7 in., fairly uniformly distributed throughout the year.

Essentially all of the land in the basin is occupied by forests on both the steeper slopes and the flatter areas in the valley. There are only a few small buildings along the streams, most of which are hunting and fishing cabins occupied only on a seasonal basis. There is no farming activity in the basin.

THE HIGHWAY

After crossing the West Branch of the Susquehanna River, Interstate 80 swings in a northwesterly direction as it enters the White Deer Creek drainage basin. It crosses the creek approximately 2.7 miles upstream of its mouth and then proceeds in a westerly direction along the north side of the valley along the base of the South White Deer Ridge as shown in Figure 1. About 8.8 miles upstream of the crossing, the highway leaves the main valley and closely follows Sand Spring Run, a tributary of White Deer Creek, for approximately 3.4 miles before leaving the basin.

Only the western 5.4 miles of highway construction were included in this study. The construction included four box culverts for the tributaries Lick Run, Mile Run, Kurtz Gap Run, and Sand Spring Run; an overpass for a local road near the Sand Spring Run crossing; and a diamond interchange at Mile Run. Upslope drainage is collected in lined channels at two points and conveyed beneath the highway. Some relocation of the channel was required for Sand Spring Run in the vicinity of its crossing.

The highway consists of two dual-lane roadways, each 24 ft wide. The shoulders adjacent to the median are 8 ft wide including a 4-ft wide stabilized portion. The outside shoulders are 12 ft wide and have a 10-ft wide paved portion. The side slopes in the cut or fill areas are 6:1 for 0- to 4-ft depths, 4:1 for 4- to 10-ft depths, and 2:1 for depths over 10 ft. The median width varies from 84 to 200 ft with the natural vegetation undisturbed everywhere possible.

THE RESEARCH PLAN

The problem of determining the suspended sediment yield in a stream system resulting from rainfall on an area undergoing highway construction may be divided into three phases. The erosion process is that involved with the detachment of soil particles and their movement from the construction area. Rainfall is one of the most important factors affecting erosion inasmuch as it is responsible for the detachment of soil particles. The ease of detachment is a function of the soil and its erodibility characteristics and the condition of the soil surface as related to its compaction, which, in turn, is related to the phase of construction and the intensity of the construction activity. The transport of particles over the exposed surface is a function of the slope length and gradient. Finally, the total yield is related to the area of the soil exposed by the construction.

The second phase is the movement of sediment from the construction area to a definite stream channel and is called the overland transport process. The slope length and gradient of the natural ground surface between the construction site and the stream are of prime importance. The antecedent moisture in the natural ground will affect the infiltration rate of the overland flow and is a factor in the quantity of sediment reaching the stream rather than being deposited on the ground surface. The density and nature of the vegetation and debris on the surface are factors with ability to trap the sediment prior to its reaching a stream.

The final phase is the stream transport process, which relates to the ability of the stream to carry the sediment load it receives from the first two processes. The variables pertinent to this phase include the discharge of the stream, channel cross-sectional characteristics, channel slope, boundary roughness, size distribution of suspended sediment, and average suspended concentration.

To study the sediment yield under a number of different conditions relative to the three problem phases required that eight stations be established on the White Deer Creek stream system as shown in Figure 2. Three of the stations, F, G, and H, were located upstream of the construction area to measure the natural sediment load transported into the reach of the stream affected by the construction.

Four continuously recording rain gauges were located within the drainage basin. Gauge 1 was located adjacent to the construction downstream of the area shown in Figure 2. Gauge 4 was located near the centroid of the basin of the upper branch of the White Deer Creek away from the construction activity. Gauges 1, 2, and 3 had approximately equal spacing along the construction area, negating the necessity of applying weighting factors to the data collected by each.

Series of soil samples were collected from the construction area at random locations. Mechanical analysis and determination of other soil properties for these samples were conducted by project personnel. From these results, approximately 50 percent of the samples were classified in the A-4 group (AASHO classification), and the remainder fell within the A-1-b and A-2-4 groups. The different soils were found throughout the construction area so that the effect of soil erodibility could not be analyzed.

The construction process was divided into several phases: clearing and grubbing, structures, embankment, drainage, and seeding and mulching. The data describing these phases were obtained from the field notes of Pennsylvania Department of Transportation inspectors and were frequently checked by site inspection by project personnel. The clearing and grubbing phase commenced in June 1968 and was completed by mid-April 1969. The bulk of the operation was completed during the summer of 1968 as shown in Figure 3. The field notes compiled the clearing and grubbing progress by highway stations. This longitudinal measurement was converted into area units by scaling widths of cleared area from aerial photographs.

The embankment work began in August 1968 and was completed by October 1969. About one-half of the total fill material was placed during the fall of 1968, whereas most of the cuts were done during the summer of 1969 (Fig. 3). The embankment progress was compiled in the field notes as the number of cubic yards of earth both removed and placed by stations. Thus the cut-and-fill operations were accurately defined as to quantity and location. The structures and drainage work data were compiled but were considered too localized to have a measureable effect on the sediment yield and are not considered in the analysis.

Final grading, seeding, and mulching began in the study area in June 1970 and was completed by August 1970. The field notes described the progress of this phase by stations, allowing accurate definition of the completion of the task. But the transition from freshly seeded and mulched surface to protective vegetative cover is not well defined. Also, some reseeding and touch-up work was performed during and following the major seeding operations, but no record was maintained of this work.

The purpose of selecting five stream stations for sediment yield measurement was to permit the study to consider different conditions of the overland transport phase. Stations B and C, located on Lick Run and Mile Run respectively (Fig. 2), received sediment directly from the construction area with no overland transport. Station D, located downstream of station E on Sand Spring Run, station A, located on White Deer Creek, and station E all received sediment from overland flow, with each having a different average distance from construction to stream. The average slope gradient of the natural ground for each of these three stations was obtained from topography maps but was not considered to be of sufficient variation for consideration in the analysis. The antecedent moisture conditions are a function of time between

Figure 1. White Deer Creek drainage basin.

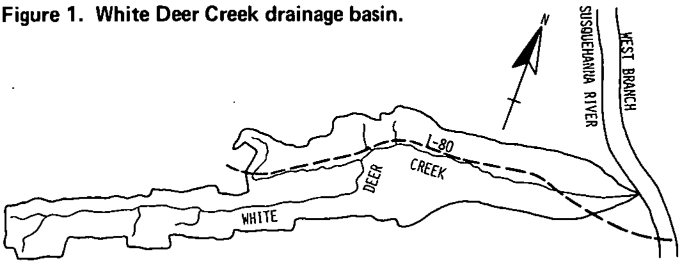


Figure 2. White Deer Creek study area.

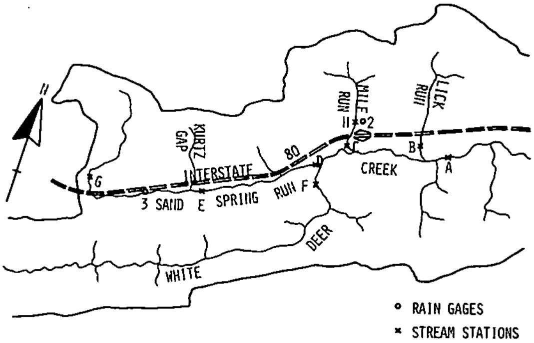
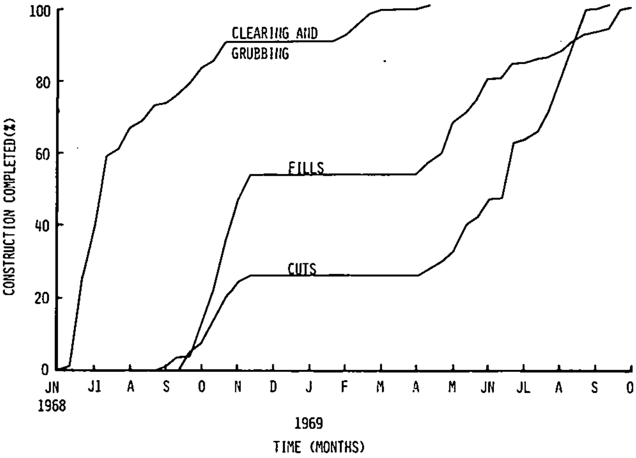


Figure 3. Construction progress.



storms, data available from rain gauges. Because the White Deer Creek drainage basin is entirely wooded, the natural ground cover factor was considered a constant for all stations and was not considered in the analysis.

Visual observations of the channel bottom at many locations in the stream system indicated that there was no accumulation of sediment as a result of the highway construction. For this reason, the only variables that were necessary for measurement of the suspended sediment load were the discharge of the stream and the average suspended sediment concentration at the measuring stations. Continuously recording stage gauges were operated at stations A, D, E, and F to yield the variation of the stage at each for every storm. These stage readings were converted to discharge by employing rating curves that had been developed by an extensive stream gauging program. The discharge hydrographs at stations B, C, G, and H were simulated from those obtained at station D. The suspended sediment concentrations during storm runoff events were obtained from sediment samples collected periodically throughout the event. They were collected with a depth-integrating, hand sampler and analyzed by project personnel. Hand samples at station A were supplemented during the summer of 1970 by samples collected every 30 min during storm events by a stage-actuated, automatic sediment sampler. The suspended sediment yield in tons at each station for each sampled storm was obtained by planimetering the areas under the sediment flow curves. The ordinates of these curves were the sediment flow rates in tons per hour obtained by multiplying the concentrations by corresponding water discharges and the appropriate conversion factor. Sediment flow and water discharge graphs at station A for three storms are shown in Figures 4, 5, and 6.

INDEPENDENT PARAMETER DEVELOPMENT

It was noted in the previous discussion that some variables important to the physical problem of sediment yield from highway construction areas could not be considered in the development of the prediction equation due to conditions in the study area. The soils were found to be relatively uniform and their effect on erosion was considered constant. Certain localized construction phases were considered to have a negligible effect on the net yield in the stream system and were ignored. The slope gradient and the natural cover of the area between the construction and the stream were considered constant in the study area. Because the stream system was apparently capable of transporting the imposed sediment load, the hydraulic properties of the channels and the size distribution of the suspended sediments were not included as variables. The remaining variables mentioned previously were measured, and their effect on sediment yield was analyzed.

Wischmeier and Smith (6) have found that the best single rainfall variable related to soil loss is the product of the total rainfall energy of a storm and its maximum 30-min intensity. They defined a rainfall factor, R, as

$$R = \frac{RE \cdot I}{100} \tag{1}$$

where RE is the total rainfall energy for the storm in foot-tons/acre and I is the maximum 30-min intensity in in./hour. The rainfall occurring during each 15-min increment of each storm for each of the four rain gauges located in the study area was compiled from the respective recording charts. These data were substituted into the equations of Wischmeier and Smith to determine rainfall factors for each gauge.

The total suspended sediment yield is obviously a function of the area of the exposed surface affected by the rainfall. For this study, area A, in acres, was that exposed by the clearing and grubbing phase of the construction. Data describing the condition in the drainage basin of each stream station at the time of a storm were obtained from the compiled construction data.

The slope length and gradient of exposed surfaces have been shown (1) to be of prime importance in soil loss computations. Highway construction is responsible for radical alterations of natural slopes with its cut-and-fill operations. An attempt to establish a representative slope length and gradient factor for the long, narrow areas over varying terrain common to this construction would be very difficult. Recognizing that side slopes are generally standardized, it was reasoned that average depth D, in yards, of cuts and fills would be a measure of slope characteristics. The transient average depth of embankment work in the drainage basin of each stream station was computed by the equation

$$D = \frac{0.00021\ E}{A} \tag{2}$$

where E is the total volume of earth moved, in cubic yards, and the constant is necessary to convert the area from acres to square yards. The embankment quantity was obtained from the compiled construction data. The minimum value of the average depth, $D = 0$, occurs after clearing and grubbing have begun but before embankment work is undertaken.

From the discussion of the overland transport phase of the problem and its treatment by the research plan, it remains, for the conditions of this study, to develop a measure of the proximity of the construction area to the stream system. A nondimensional parameter, proximity factor P was rationalized as being an excellent measure of this relationship. It was defined as

$$P = \frac{A_o}{A} \tag{3}$$

where A_o is the surface area between the upslope side of the construction and the stream, in acres. The overland surface area for each stream station was obtained by planimetering highway location plans. The minimum value of the factor, $P = 1$, occurs when a stream crosses a construction area so that the sediment contribution is direct with no overland flow.

DERIVATION OF THE PREDICTION EQUATION

The objective of this study was to develop a mathematical description of the relationship between the increase in suspended sediment yield in a stream system and highway construction occurring in its drainage basin. Due to the nature of the problem, which defies theoretical analysis, it was anticipated that the relationship would be established by the multiple regression analysis of the data collected in the White Deer Creek drainage basin during the construction of Interstate 80 through it.

The prediction equation to be developed from these data would generally be assumed to be of the form

$$Q_s = K\ R^a\ A^b\ D^c\ P^d$$

where Q_s is the suspended sediment yield at a stream station, in tons, and K, a, b, c, and d are empirical constants. Rational study of the several independent factors permits some modifications of this form of equation. Sediment would be transported by the stream following clearing and before embankment work, when $D = 0$. It is observed that the model would not satisfy this requirement. Thus, the D^c factor was converted to the form c^D, for a new model. A preliminary plot of log Q_s versus log A, while maintaining the other factors constant, indicated that the relationship was not exponential but approximately logarithmic. Therefore, the A^b factor was converted to the form $(\log A)^b$. Examination of the expected relationships between Q_s and the independent variables shows that Q_s should increase with increasing R, A, and D and decrease with increasing P. Thus, the signs of the exponents a, b, and D should be positive and the exponent of d negative.

The new model equation for relating the chosen variables is rationally of the form

$$Q_s = \frac{K\,R^a\,(\log A)^b\,c^D}{P^d} \qquad (4)$$

The multiple regression analysis was performed with the logarithmic transformation of Eq. 4.

$$\log Q_s = \log K + a \log R + b \log (\log A) + D \log c - d \log P \qquad (5)$$

Before the regression equation was developed, several special considerations were applied to the data. Some storms were omitted for the following reasons as presented by Brokaw (7):

1. Exclusion of all storms combining rain and snow,
2. Exclusion of those storms with R less than 0.5 foot-ton-in./acre-hour and/or less than ¼-in. of measured rainfall,
3. Exclusion of all storms occurring when the soil was saturated with frost,
4. Exclusion of all storms separated by less than 48 hours, and
5. Inclusion of storms separated by less than 24 hours as one event.

In addition, some storms were omitted due to an insufficient number of suspended sediment concentration values that were necessary for the determination of Q_s.

Rainfall factor values for each storm were generally determined for station A by averaging R values from rain gauges 1, 2, 3, and 4; for station B by averaging R values from rain gauges 1 and 2; for C by using R values from 2; for D by averaging the R values from 2 and 3; for E by using R values from 3; for F by using R values from 4; for G by using R values from 3; and for H by using R values from 2 (Fig. 2).

The measured values of Q_s at the stations affected by the construction were adjusted by subtracting the natural loads as measured at the stations away from construction. For example, the adjusted suspended sediment loads at station E were found by subtracting the measured values at station G from the measured values at station E. Generally, the natural loads measured at stations G and H were insignificant.

Vice, Guy, and Ferguson (5) adjusted their sediment yield data for the seeding and mulching conditions. They assumed that sediment yield was reduced 50 percent upon application and further reduced by 80 percent as a fairly well-established sod cover developed. The sediment data for this study were similarly adjusted beginning with seeding and mulching in June 1970 and continuing until the end of the study period.

Following the noted exclusions and adjustments, the number of sets of data for the various stream stations noted below was available for the analysis:

Station	Data Sets
A	22
B	14
C	12
D	19
E	19
Total	86

A graphical multiple regression analysis was performed with these 86 sets of data using Eq. 5 as the model. The solution was transformed back to the form of Eq. 4, yielding

$$Q_s = \frac{0.034\, R^{1.5}\, (\log A)^{2.45}\, (3.0)^{D}}{P^{0.72}} \qquad (6)$$

which was found to have a standard error of estimate of 24 percent. Equation 6 is the prediction method for suspended sediment yield in a stream system from rainfall-induced erosion of soil exposed by highway construction.

DISCUSSION OF RESULTS

The general validity of the relationship developed in Eq. 6 may be questioned relative to the adequacy of the range of independent variable values tested in the field study. Table 1 gives the magnitudes of pertinent parameters for each of the stream stations affected by the highway construction. Wischmeier and Smith (1) have compiled the expected magnitudes of single-storm rainfall factors for representative points throughout the United States. Interpolating from values listed for Pennsylvania to the White Deer Creek valley, the return period for the maximum measured R would be approximately 2 years. The range of exposed area included in the analysis was from 3.3 to 168.75 acres, which would appear to be adequate for general representation. Obviously, larger D values may be encountered at other construction sites, but the range tested in this study, from 0 to 3.2 yd, would include conditions encountered at many locations. Interstate 80 is relatively near White Deer Creek as indicated by small proximity factor values. As the sediment yield decreased with increasing proximity factor, the more important conditions were tested.

Of the four independent variables included in Eq. 6, the rainfall factor has the greatest effect on the sediment yield from the physical problem viewpoint. The magnitude of R will be relatively large, and the exponent value greater than one in the equation indicates its importance. The exposed area and average depth of embankment factors describe the magnitude and intensity of the transient construction activity. As such, they indicate the erodibility potential available to the rainfall factor. Again from the physical problem view, the A term is the most significant with the D factor acting to modify its effect. D indicates the construction activity on an exposed area that must exist first. The three terms in the numerator of Eq. 6 indicate a measure of the quantity of sediment leaving the construction area. This quantity is modified by the conditions that effect the overland transport process. The proximity factor P quantifies the reduction of sediment reaching a stream through this process. It would be a very important factor to the engineer during highway location studies.

The discussion of the overland transport process in an earlier section included the effect of antecedent moisture in the natural ground. Unfortunately, there were not a sufficient number of samples to discern the effect of this variable. It undoubtedly was responsible for some of the scatter that was measured by the standard error of estimate.

The constant coefficient in Eq. 6 includes the effect of the particular type of soil that was found on the construction area in the White Deer valley. To extend the application of this prediction method to other areas, it will be necessary to evaluate the soil erodibility effect. It may be possible to incorporate the soil erodibility factor developed for the universal soil loss equation into the coefficient of Eq. 6. That factor was evaluated so that, if all other conditions are constant, its effect on soil loss was linear. Recent research (8) has generalized the factor for all types of soils. Data are currently being collected at three other drainage basins in Pennsylvania, which should permit the evaluation of the soil erodibility effect.

The constant coefficient in Eq. 6 also includes the effect of the slope gradient and the nature of the cover of the natural ground between the construction area and the stream system in the White Deer Creek drainage basin. The data being

Figure 4. Discharge and sediment flow at station A, September 6, 1968.

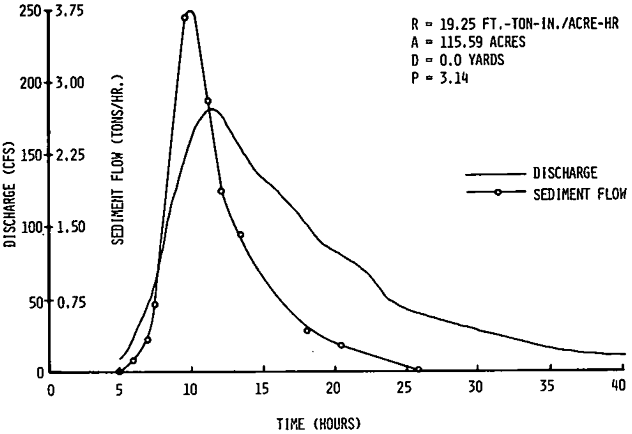


Figure 5. Discharge and sediment flow at station A, August 19, 1969.

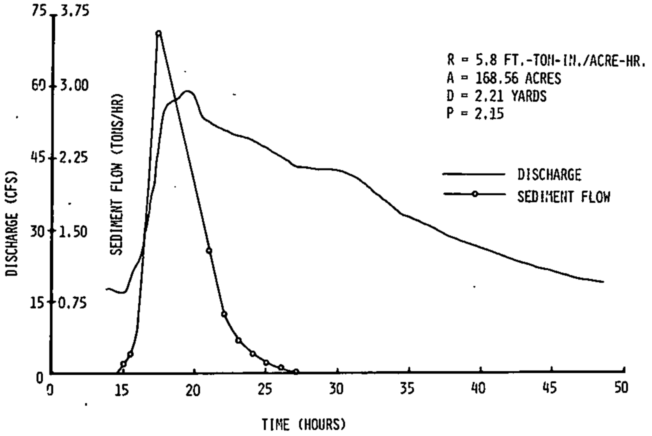


Figure 6. Discharge and sediment flow at station A, August 21, 1970.

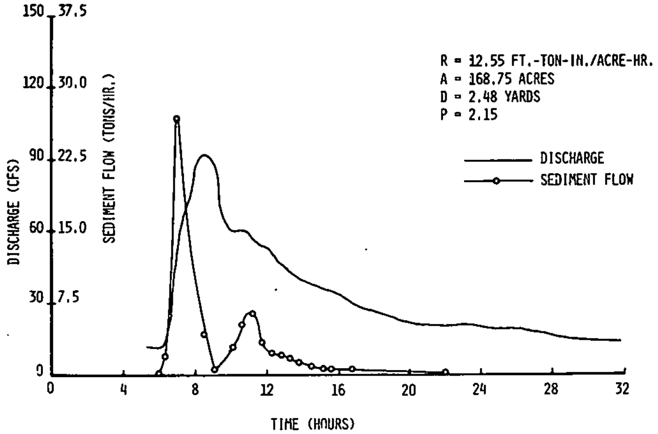


Table 1. Extreme parameter values from the study area.

Stream Station	R(ft-ton-in./acre-hour) Maximum	Minimum	A Maximum (acres)	D Final (yards)	P Final	Highway Length Upstream (miles)
A	24.7	0.70	168.75	2.48	2.15	5.42
B	28.1	2.15	5.95	2.67	1.0	0.28
C	28.1	2.15	4.93	3.2	1.0	0.19
D	21.7	0.58	110.93	2.7	2.16	3.38
E	21.7	0.52	59.65	2.17	1.09	1.75

collected in the other three basins may be utilized to establish the effect of these factors. These areas each have different terrain and land uses from those found in White Deer Creek.

CONCLUSIONS

An equation has been developed that may be employed to predict the suspended sediment load carried by a stream system during the period of rainfall-induced erosion of disturbed soils common to highway construction. Equation 6 considers the effect of the erosive power of the rainfall; the effect of the important construction phase parameters, area of exposed soil surface, and average depth of embankment; and the effect of the proximity of the construction to the stream system.

It may be employed for the prediction of sediment yield from construction areas in other drainage basins if they have soils, terrain, and land use similar to those found in the White Deer Creek valley. The effects of these three factors are contained in the constant coefficient of Eq. 6. Evaluation is currently being undertaken by similar studies in three additional drainage basins.

Highway development often occurs in conjunction with the construction of housing developments, shopping centers, factories, and other urban expansions. These sites are often blamed for the pollution of adjacent waterways with highways receiving the brunt of the accusation. This equation may be used to define the portion of the sediment yield caused by the highway construction. An engineer may establish the location of a proposed highway in a drainage basin for minimum sediment yield by application of Eq. 6. Increasing the distance from a stream increases P but would usually increase D, due to rougher terrain. An optimum location, from the sediment yield aspect, could be found. Sediment control on construction sites is receiving increasing attention. Equation 6 was developed for the condition of uncontrolled construction and thus could be used as the basis for comparison to evaluate the effectiveness of control methods.

ACKNOWLEDGMENTS

This paper is based on part of a study conducted under the sponsorship of the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Pennsylvania Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Acknowledgment is also made for the invaluable assistance rendered by the personnel of the Pennsylvania Department of Transportation, District 3-0, Montoursville. W. Curtis Chandler, Harry Kitch, and J. Staats Brokaw, research assistants, David Wright, research engineer, and Roger Chappel, technician, have each contributed essential effort toward the conduct of the study.

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