Rainfall Factors That Affect Erosion

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Soil erosion from highway construction sites should be considered a significant environmental factor in the design of highway drainage systems. Although the problem of predicting soil erosion has been studied rather extensively over the past 40 years, there is still no consensus as to which predictive method is superior. Many causal factors contribute to soil erosion, some of them misunderstood and some mistreated in application. This paper isolates the most significant factor, rainfall, and demonstrates how that factor has evolved as the needs of researchers have changed. Some of the literature on the subject is reviewed, from the first studies performed to the present time. Three distinct rainfall parameters—30-min maximum rainfall intensity, rainfall energy, and direct runoff—have proved to be good indicators of soil erosion from land surfaces, and the time distribution of rainfall has recently proved to be of relative significance in predicting sediment yield.

Research on the various causal factors of soil erosion has been studied since the early 1920s. For the most part, this research has been concerned with agricultural soil erosion. Not until the mid-1960s was the problem of soil erosion from construction areas addressed.

Excessive soil loss reduces crop productivity and is naturally of major concern to farm owners and operators. However, although soil loss from construction sites is often many times greater than that from comparable farm lands, land developers and construction contractors have had less incentive for control. Consequently, soil erosion from construction sites has not been effectively checked and, in rapidly developing locations such as the eastern United States, it is creating serious environmental problems.

In September 1972 the Pennsylvania Department of Environmental Resources adopted rules and regulations for the control of soil erosion to protect the state's natural water resources. Because of similar environmental and ecological constraints imposed by other federal, state, and local authorities, engineers must now be able to predict the sediment yield from a proposed highway construction project. Although many causal factors of soil erosion and sediment yield have been studied, this paper focuses only on the rainfall parameters that are significant in the erosion process.

In the development of methods for predicting erosion, rainfall has always been considered, and usually verified, to be the most significant single index of erosion. Simple expressions were used in the early predictive methods, but as research techniques improved more complex factors evolved. Today, thanks to sophisticated high-speed computers and statistical analysis, complex parameters pose no real difficulty in computation.

Essentially, there are three rainfall parameters that are important in determining soil erosion and sediment yield: rainfall intensity, rainfall energy, and direct runoff. The time distributions of these parameters may also be significant.

RAINFALL INTENSITIES

Intense storms possess high kinetic energy. A high-intensity storm contains a greater percentage of energy than one of moderate to low intensity and is the principal cause of soil erosion.

Initial research dealt with artificial rainfall on well-calibrated soil plots. These initial investigations found raindrop size and amount, storm duration, and velocity of raindrops to be important parameters in predicting soil erosion. However, as further studies (1, 2, 3) showed, rainfall intensity was the most dominant rainfall factor.

Smith and others (4) studied 5, 15, and 30-min maximum rainfall intensities to determine which intensity was the most important in producing maximum rate of runoff for 79 storms over an 8-year period. Their research, which took into account antecedent soil moisture, found that the 30-min maximum rainfall intensity had the greatest effect on the maximum rate of runoff. In the late 1940s and early 1950s, more detailed studies evolved. Musgrave (5) developed an erosion-prediction method based on rainfall, flow characteristics, soil characteristics, and vegetal cover. In studying erosion from agricultural lands, Musgrave found rainfall to be the primary causal factor of erosion. Hays (6) also found in his studies that a very good relation existed between the maximum amount of rainfall occurring within any 30-min period and the amount of soil that was eroded during the duration of the storm. Other factors being equal, erosion was found to be approximately proportional to $P_{30}^{1.75}$, where P_{30} represents the maximum amount of rainfall (in inches) occurring in any 30-min period. (The data presented here were calculated in U.S. customary units only; therefore, values are not given in SI units.)

A statistical analysis performed by Foster (7) used nine indices of rainfall intensity: four simple, frequently used indexes and five compound indexes. The four common measures were the 5, 15, and 30-min intensities and the average intensity, which was defined as the total rainfall (in inches) divided by the elapsed time (in seconds). Foster (7)—like Hays and others (6) and Smith and others (4)—found that the maximum 30-min rainfall was the most significant rainfall factor.

A sample of 244 storms that occurred at six highway construction sites in Pennsylvania were analyzed to determine the level of significance of different rainfall intensities. The table below summarizes the statistics for P_{TOT} (total precipitation) and P_{15}, P_{30}, P_{60}, and P_{180} (15, 30, 60, and 180-min maximum rainfall intensities in inches per hour respectively). The table ranks the correlation coefficients of each measure of precipitation to sediment yield divided by the correlation coefficient for P_{180} (1 in = 25.4 mm).

Precipitation (in/h)	Correlation Coefficient: Total Sediment	Correlation Coefficient: Mean Sediment Concentration
15	1.73	2.37
30	1.41	2.11
60	1.07	1.61
180	1	1
Total	0.17	0.08

The data in the table show that shorter duration rainfall intensities are more correlated to sediment yield than are greater intensities. However, as other studies (4, 6, 7) have shown, maximum 30-min rainfall is as good, for all practical purposes, as any other single rainfall parameter.

Table 1. Kinetic energy of natural rainfall.

Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]
0.00	0	0.40	784	0.80	884	3.0	1074	7.0	1196
0.01	254	0.41	788	0.81	886	3.1	1079	7.1	1198
0.02	354	0.42	791	0.82	887	3.2	1083	7.2	1200
0.03	412	0.43	795	0.83	889	3.3	1088	7.3	1202
0.04	453	0.44	798	0.84	891	3.4	1092	7.4	1204
0.05	485	0.45	801	0.85	893	3.5	1096	7.5	1206
0.06	512	0.46	804	0.86	894	3.6	1100	7.6	1208
0.07	534	0.47	807	0.87	896	3.7	1104	7.7	1209
0.08	553	0.48	810	0.88	898	3.8	1108	7.8	1211
0.09	570	0.49	814	0.89	899	3.9	1112	7.9	1213
0.10	585	0.50	816	0.90	901	4.0	1115	8.0	1215
0.11	599	0.51	819	0.91	902	4.1	1119	8.1	1217
0.12	611	0.52	822	0.92	904	4.2	1122	8.2	1218
0.13	623	0.53	825	0.93	906	4.3	1126	8.3	1220
0.14	633	0.54	827	0.94	907	4.4	1129	8.4	1222
0.15	643	0.55	830	0.95	909	4.5	1132	8.5	1224
0.16	653	0.56	833	0.96	910	4.6	1135	8.6	1225
0.17	661	0.57	835	0.97	912	4.7	1138	8.7	1227
0.18	669	0.58	838	0.98	913	4.8	1141	8.8	1229
0.19	677	0.59	840	0.99	915	4.9	1144	8.9	1230
0.20	685	0.60	843	1.0	916	5.0	1147	9.0	1232
0.21	692	0.61	845	1.1	930	5.1	1150	9.1	1233
0.22	698	0.62	847	1.2	942	5.2	1153	9.2	1235
0.23	705	0.63	850	1.3	954	5.3	1156	9.3	1237
0.24	711	0.64	852	1.4	964	5.4	1158	9.4	1238
0.25	717	0.65	854	1.5	974	5.5	1161	9.5	1240
0.26	722	0.66	856	1.6	984	5.6	1164	9.6	1241
0.27	728	0.67	858	1.7	992	5.7	1166	9.7	1243
0.28	733	0.68	861	1.8	1000	5.8	1169	9.8	1244
0.29	738	0.69	863	1.9	1008	5.9	1171	9.9	1246
0.30	743	0.70	865	2.0	1016	6.0	1174		
0.31	748	0.71	867	2.1	1023	6.1	1176		
0.32	752	0.72	869	2.2	1029	6.2	1178		
0.33	757	0.73	871	2.3	1036	6.3	1181		
0.34	761	0.74	873	2.4	1042	6.4	1183		
0.35	765	0.75	875	2.5	1048	6.5	1185		
0.36	769	0.76	877	2.6	1053	6.6	1187		
0.37	773	0.77	878	2.7	1059	6.7	1189		
0.38	777	0.78	880	2.8	1064	6.8	1192		
0.39	781	0.79	882	2.9	1069	6.9	1194		

Note: 1 in = 25.4 mm; 1 ft-tonf = 2.7 MJ; 1 acre = 0.4 hm^2.

[a] Measured in foot-ton-force per acre per time unit for 1 in of rain.

Table 2. Procedure for determining total energy of a rainstorm.

Time (min)	Accumulated Rainfall (in)	Incremental Rainfall (in)	Intensity (in/h)	Energy[a]	Total Energy of Storm (ft-tonf/acre/in of rain)
0					
10	0.04	0.04	0.25	717	28.7
20	0.21	0.17	1.00	916	155.7
30	0.29	0.08	0.50	816	65.3
40	0.37	0.08	0.50	816	65.3
50	0.41	0.04	0.25	717	28.7
60	0.43	0.02	0.12	611	12.2
					355.9

Note: 1 in = 25.4 mm; 1 ft-tonf = 2.7 MJ; 1 acre = 0.4 hm^2.

[a] Measured in foot-ton-force per acre per time unit for 1 in of rain (from Table 1).

RAINFALL ENERGY

In the early 1950s, because of an increased interest in land-use practices, new impetus was generated to develop more precise techniques for predicting soil erosion. Rainfall intensity by itself was no longer a valid representation of the rainfall factor used in many of the soil-erosion equations of that period. For the first time, a concentrated effort was focused on the mechanics of the soil-erosion process. In an early study, Ellison (8, 9, 10, 11) showed that the impact of raindrops on the soil surface starts erosion by detaching the soil particles, which are then transported by overland flow. In 1954 the Soil and Water Conservation Research Division of the Agricultural Research Service initiated a program to summarize for further analysis all available runoff and soil-loss data on a national basis. Studies conducted under that program pointed out that greater accuracy could be achieved in soil-loss prediction equations applied to individual storms if a measure of rainfall energy were included as a variable. Both the efficiency and the simplicity of such equations were further improved by using terms that measure the interaction effects among variables.

In an attempt to improve soil-loss prediction, Wischmeier and Smith (12) related rainfall energy to soil erosion. Using a concept of rainfall energy that is based on studies such as that of Laws and Parsons (14), which relates drop size to rainfall intensity, they developed a relatively simple procedure for computing the approximate rainfall energy of a storm. If rainfall energy is to be used as the rainfall parameter in estimating soil erosion, then the kinetic energy of a rainstorm is the appropriate factor. Kinetic energies in foot-ton-force per acre per time unit for 1 in of rain, for natural rainfall at various intensities, are given in Table 1. Wischmeier developed the following regression equation from which the values in Table 1 were derived:

$$Y = 916 + 331 \log_{10} X \tag{1}$$

where

- Y = kinetic energy (in foot-ton-force per acre per time unit for 1 in of rain) and
- X = rainfall intensity (in inches per hour).

To compute Wischmeier's energy value for a rainstorm, Table 1 is used in conjunction with recorded rain-gauge data. Given the time and accumulated rainfall values from a recording rain gauge, the energy of a storm can be obtained as follows:

1. Determine the rainfall, in inches, for each time increment.
2. Determine the rainfall intensity, in inches per hour, for each time increment.
3. Determine the kinetic energy, in foot-ton-force per acre per time unit for 1 in of rain, by using Table 2.
4. Multiply the values for accumulated rainfall by the energy values and add the resulting values to determine the total energy of the storm, in foot-ton-force per acre for 1 in of rain.

Table 2 gives an example of the use of this procedure.

Two rainstorms of equal volume falling on the same field often produce different amounts of soil loss. To analyze and solve soil-erosion problems of this kind it is necessary to know which rainfall characteristics are responsible for such differences. Wischmeier approached this problem primarily on a mathematical basis by using multiple regression theory. Combinations of rainfall characteristics, interaction effects, antecedent soil-moisture conditions, and soil-compaction terms were investigated in exploratory studies. The most significant variable found for predicting soil loss from cultivated fallow soil was the product of the total kinetic energy of a storm times its maximum 30-min intensity. This product, called the erosion index (or EI variable), measures the interaction effect of the two most prominent rainfall characteristics. Because it is used by so many researchers as the rainfall parameter for predicting soil erosion, the index is well documented in the literature and is a good measure of the erosion-producing capacity of a soil.

DIRECT RUNOFF

Rainfall intensity, the parameter initially used in determining soil loss, is highly correlated with soil erosion but it oversimplifies the problem. The ability to predict soil loss was substantially improved when Wischmeier and Smith published their universal soil-loss equation (13). In this equation they combined rainfall energy with 30-min maximum rainfall intensity as the significant rainfall parameter. The intended application of the equation was to predict potential soil loss from agricultural fields.

Although rainfall energy is generally highly correlated with runoff, it is not affected by antecedent soil moisture. Therefore, if soil moisture is low, high-energy rainstorms may produce little or no runoff. With no runoff there can be no sediment yield.

To design sediment-control devices the highway engineer must know how much sediment is transported to the drainage system. Wischmeier and Smith's equation predicts potential soil loss but not the amount of sediment at a particular location in the drainage area; the equation therefore needs to be modified by a delivery ratio (15, 16). Because the delivery ratio is a complex function of watershed characteristics, such as drainage area, stream slope, watershed shape, and runoff, how and why it varies have not been well documented in the literature. Because of the unknown variability and sensitivity of the delivery ratio and the fact that the soil-erosion process may not be the same for fallowed agricultural lands as it is for highly compacted soil conditions at highway construction sites, researchers have continued to investigate new rainfall parameters.

Many recent studies have used multiple regression analysis to develop parametric equations. The most significant rainfall parameter currently being studied is the runoff factor (17). Williams and others (18) found a runoff factor that proved to be superior to rainfall for predicting sediment concentrations from five small watersheds in the Texas Blacklands. In 1972 Williams and Berndt (19) modified the universal soil-loss equation for watershed application by replacing the rainfall factor of Wischmeier with a runoff factor. Williams had shown in an earlier study that runoff is more highly correlated to sediment loss than is rainfall.

The Hydraulics Division Committee on Sedimentation of the American Society of Civil Engineers (ASCE) has stated that runoff is the best single parameter in predicting soil erosion (20). The use of runoff rate for determining sediment yield is also appealing because many short-term runoff records for watersheds throughout the country can be extended by applying an assumed rainfall-runoff relation to long-term rainfall records. According to the ASCE committee, it is reasonable to assume that the best rainfall parameter would only approach a factor that expresses runoff rates or volumes because runoff represents the integrated effect of all rainfall and antecedent soil-moisture conditions.

TIME DISTRIBUTION OF STORM RAINFALL

The time distribution of rainfall parameters may be an important variable in the prediction of sediment erosion. The characteristics of a design storm must include the amount, the duration, the season of the year, and the time-distribution pattern of rainfall. Figure 1 shows time-distribution curves for three types of storms. Figure 2 shows the difference between the time-distribution curves produced by an early-peaking storm (type 1) and a late-peaking storm (type 3) for one of the watersheds currently being studied.

Because a designer may be interested in synthesizing a flood hydrograph, the time distribution of rainfall can be important. In addition, because runoff is affected by the pattern of rainfall distribution, sediment yield may also be affected by rainfall distribution even though energy is independent of storm type. For the 244 storms studied, runoff is the rainfall parameter most highly correlated to sediment erosion.

In his research Wischmeier expected the relation of the EI value to soil loss to be influenced by the sequence of rainfall intensities within a storm. In 1958, Wischmeier and Smith (12) classified storms according to type as advanced (early peaking), intermediate (mean), and delayed (late peaking), depending on the relative time of occurrence of the period of greatest storm intensity. They found no correlation between the type of storm and the unexplained residuals of soil losses in the data and concluded that storm type did not influence the relation of soil loss to EI.

Our study, however, has found the type of storm to be significant at the 85 percent confidence level when storms are observed on an individual basis. Late-peaking storms appear to be more erosive than average and early-peaking storms. Because late-peaking storms generally yield more runoff with higher peaks, this further reinforces the fact that runoff is a critical predictor of sediment yield.

The data given in Table 3 illustrate the importance of the relative time of occurrence of the period of greatest storm intensity. Both storms have the same characteristics, the same kinetic energy, and the same EI, but they are distributed differently. The late-peaking storm will yield more runoff and ultimately produce a higher sediment yield. Maximum 30-min intensity for the early-peaking and late-peaking storms in Table 3 is determined as follows:

$$I_{30_{EP}} = 0.385 \text{ in}/0.5 \text{ h} = 0.77 \text{ in/h} \quad (2)$$

$$I_{30_{LP}} = (0.4 - 0.015)/0.5\ h = 0.77\ in/h \quad (3)$$

$$EI_{EP} = 366.57(0.77) = 282.26 \quad (4)$$

$$EI_{LP} = 366.57(0.77) = 282.26 \quad (5)$$

The relative increase of sediment yield from a late-peaking storm relative to that from an early-peaking storm is shown in Figure 3. (Because the relation is still being developed, this figure should be used only as a guide.) Figure 3 shows the significance of selecting a late-peaking storm over other distributions. If a design storm is used that has a high frequency of occurrence, the increase in sediment yield will be substantial if a late-peaking distribution is selected.

Figure 1. Time-distribution curves for rainfall for three types of storms.

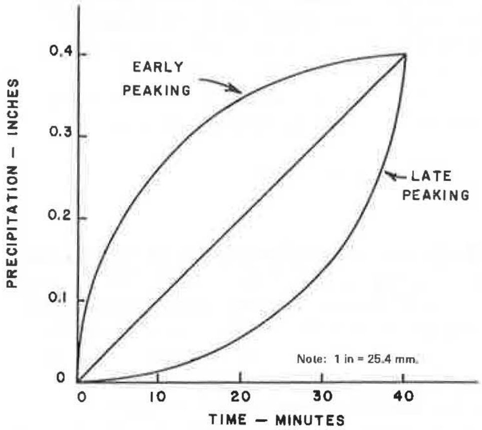
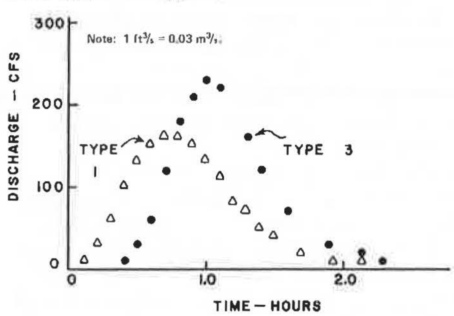


Figure 2. Hydrographs for early-peaking (type 1) and late-peaking (type 3) storm distributions.



CONCLUSIONS

The three rainfall factors predominantly used to predict soil erosion are 30-min maximum rainfall intensity, rainfall energy, and runoff factor. The 30-min rainfall intensity is the simplest factor to use. The rainfall energy factor developed by Wischmeier and Smith (12) has proved to be an excellent parameter for predicting soil erosion from agricultural lands. However, recent studies have shown that runoff may be the most significant factor for predicting erosion from highway construction sites. If runoff is to be used and if a design hydrograph is needed to size the appropriate erosion-control device, then the time distribution of the design rainfall may also be important.

Figure 3. Percentage increase of sediment yield from late-peaking storm over sediment yield from early-peaking storm.

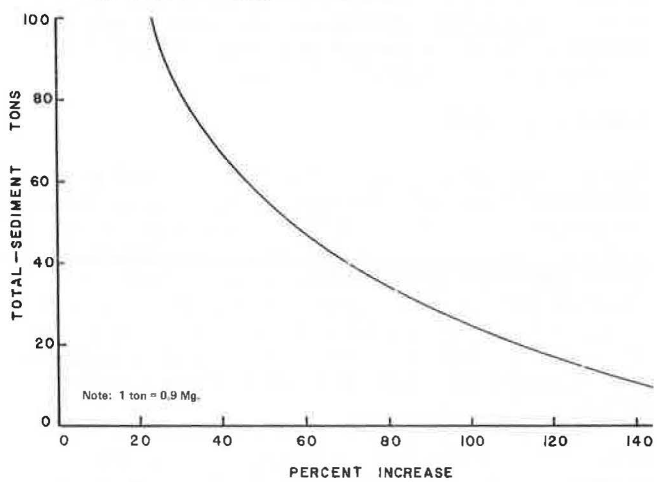


Table 3. Total storm energy of late-peaking and early-peaking storms.

Storm Type	Time (min)	Accumulated Rainfall (in)	Incremental Rainfall (in)	Intensity (in/h)	Energy[a]	Total Energy of Storm (ft-tonf/acre/in of rain)
Late-peaking	0					
	5	0.005	0.005	0.06	512	2.56
	10	0.015	0.010	0.12	611	6.11
	15	0.030	0.015	0.18	669	10.04
	20	0.055	0.025	0.30	743	18.58
	25	0.09	0.035	0.42	791	27.69
	30	0.135	0.045	0.54	827	37.22
	35	0.205	0.070	0.84	891	62.37
	40	0.400	0.195	2.34	1036	202.02
						366.57
Early-peaking	0					
	5	0.195	0.195	2.34	1036	202.02
	10	0.265	0.070	0.84	891	62.37
	15	0.310	0.045	0.54	827	37.22
	20	0.345	0.035	0.42	791	27.69
	25	0.370	0.025	0.30	743	18.58
	30	0.385	0.015	0.18	669	10.04
	35	0.395	0.010	0.12	611	6.11
	40	0.400	0.005	0.06	512	2.56
						366.57

Note: 1 in = 25.4 mm; 1 ft-tonf = 2.7 MJ; 1 acre = 0.4 hm^2.

[a] Measured in foot-ton-force per acre per time unit for 1 in of rain (from Table 1).

ACKNOWLEDGMENTS

This paper is part of a literature review being conducted for the research project, "Implementing a Procedure to Predict Sediment Flow From Highway Construction Sites," sponsored by the Pennsylvania Department of Transportation. The opinions, findings, and conclusions expressed are ours and not necessarily those of the Federal Highway Administration, U.S. Department of Transportation, or the Pennsylvania Department of Transportation.

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Publication of this paper sponsored by Committee on Environmental Factors Except Frost.