III. HYDROLOGIC ANALYSIS

3.1 Introduction

A hydrologic analysis is used to establish the design flow of a hydraulic structure. For diversion structures it is adequate to estimate the magnitude of the peak flow or flood at the required frequency for a particular drainage area. The frequency or return periods for ephemeral, intermittent and perennial streams were given in Table 1.1 and are summarized in Table 3.1.

If an adequate floodplain exists, regulations allow designing the channel and floodplain to carry the required flow, provided the channel capacity is at least equal to the capacity of the unmodified stream channel immediately upstream and downstream of the diversion. Therefore, a reasonable approach in some cases is to compute the design discharge for a lesser event than stated in Table 3.1 and compare it to the estimated unmodified channel capacity. If the values are reasonably close, then it is realistic to design based on this value. If not, a larger event must be used.

Development of the entire runoff hydrograph required for some hydraulic structures is somewhat involved. However, estimation of peak discharge required for diversion channel design is generally easier and there are a number of relatively simple methods available for use. Determining the method to use depends on the available data and the applicability of a given relationship to the design conditions. For a gaged watershed, the estimate is made by a hydrologic analysis of the drainage area characteristics, climatic characteristics and the accumulated streamflow data; however, most smaller drainages associated with diversion design are ungaged and an estimate of the design flow must be made from limited topographic and climatic data.

The primary physical characteristics that must be considered in selecting an applicable method for surface mine operations in the Eastern Coal Province are steep slopes and relatively small watershed area. Many of the available methods for peak flow estimation have been developed for moderately sloped, large-area watersheds. No single method examined was exactly tailored to meet the requirements for surface mine operations. However, since most diversion structures are small engineering structures dealing with acreages typically less than 200, and located in rural areas, the application of any one of these methods is probably acceptable.

The recommended methods are the Rational Method and the method described in SCS TP-149. The Rational Method is probably the most commonly used method

Table 3.1. Hydrologic Recurrence Interval and Design Event.

	Overland Flows, Shallow Groundwater Flows Ephemeral Streams	Perennial and Intermittent Streams
Permanent	10-year, 24-hour	100-year, 24-hour
Temporary	2-year, 24-hour	10-year, 24-hour

in the Eastern Coal Province. The SCS TP-149 is considered to be a more accurate method, and yet a relatively simple alternative to the Rational Method. While only these two methods are described in this manual, it is expected that designers will apply sound judgement and where warranted, apply more complex methods. Designers frequently determine peak rates by more than method and use judgment for selection of the design value. In some states the regulatory agencies may even dictate the preferred method.

3.2 Rational Method

The Rational Method is a common method for peak flow estimation; however, it has many limitations that must be considered. These limitations are discussed by McPherson (1969) and others. The basic problem is the great oversimplification by the equation of a complicated runoff process; however, because of the simplicity of the Rational Method, it continues to be a widely used technique.

The Rational formula is

$$Q = C\ i\ A \tag{3.1}$$

where Q is the peak flow rate in cubic feet per second (cfs), C is a dimensionless coefficient, i is the rainfall intensity in inches per hour (iph) for the design return period, and A is the drainage area in acres. Values for i can be determined from U.S. Weather Bureau Technical Paper 40 (1961). Appendix A provides these figures for the geographical area of OSM Regions I and II and for the design return periods required in diversion design. To be dimensionally correct, a conversion factor of 1.008 should be included in Equation 3.1 to convert acre-inches per hour to cfs; however, this factor is generally neglected.

The assumptions used in developing the Rational Method are:

1. The rainfall occurs at a uniform intensity over the entire watershed.

2. The rainfall occurs at a uniform intensity for a duration equal to the time of concentration, (t_c).

3. The frequency of the runoff equals that of the rainfall used in the equation.

The time of concentration (t_c) is defined as the time required for water to flow from the most remote (in time of flow) point in the watershed to the

point in consideration once the soil has become saturated and minor depressions are filled. To satisfy assumption 2, the time of concentration must be known to establish the proper value of intensity in formula 3.1. Accurately evaluating the time of concentration is one of the major problems in using the Rational formula. Table 3.2 presents t_c values for small watersheds based on a commonly used formula (Kirpich, 1940). Figures 3.1 and 3.2 provide nomographs for computing t_c that incorporate the character of the ground surface.

After estimating the time of concentration, the rainfall intensity for a duration equal to that time must be established. The U.S. Weather Bureau TP 40 charts in Appendix A are only for durations of 1 and 24 hours. The rainfall amount for a different duration can be established from these charts. If the duration established by the time of concentration is longer than one hour, the procedure is to plot the one- and 24-hour amounts for the given return period on semilog paper and interpolate by a straight line the required value. If the duration is less than one hour, the rainfall amount from the one-hour chart is multiplied by the conversion factor in Figure 3.3. The intensity in iph can then be established.

The coefficient C, called the runoff coefficient and defined as the ratio of the peak runoff rate to the rainfall intensity, is also difficult to determine. Studies have shown that C depends on the infiltration rate, surface cover, channel and surface storage, antecedent conditions, and rainfall intensity. The difficulty in lumping all these factors into one coefficient is apparent. If one C value is not applicable to the entire drainage area, an area weighted average can be established from

$$\bar{C} = \frac{\Sigma C_i A_i}{\Sigma A_i} \tag{3.2}$$

where Σ is the symbol for a summation and C_i is the coefficient applicable to the incremental area A_i. Numerous tables of C values for urban areas exist. Table 3.3 presents a table of C values developed for rural areas (Schwab et al., 1971). This table is the one found most applicable to surface mine conditions. In reviewing some of the mine plans submitted in OSM Regions I and II, it was observed that C values of 0.15 and 0.50 were commonly used for undisturbed and disturbed mine areas, respectively. According to Table 3.3, these values are reasonable only in relatively flat terrain.

Table 3.2. Time of Concentration for Small Watersheds[a]

Maximum Length of Flow (ft)	Time of Concentration (min) Watershed Gradient (percent) 0.05	0.1	0.5	1.0	2.0	5.0
500	17	13	7	6	4	3
1,000	30	23	12	9	7	5
2,000	51	39	21	16	12	9
4,000	86	66	36	27	21	15
6,000	118	90	49	37	29	20
8,000	147	113	61	46	36	25
10,000	175	134	72	55	42	30

[a]Computed from $t_c = 0.0078\ L^{0.77}\ S^{-0.385}$, where L is the maximum length of flow in feet, S is the watershed gradient in feet per foot, and T_c is the time concentration in minutes (Kirpich, 1940).

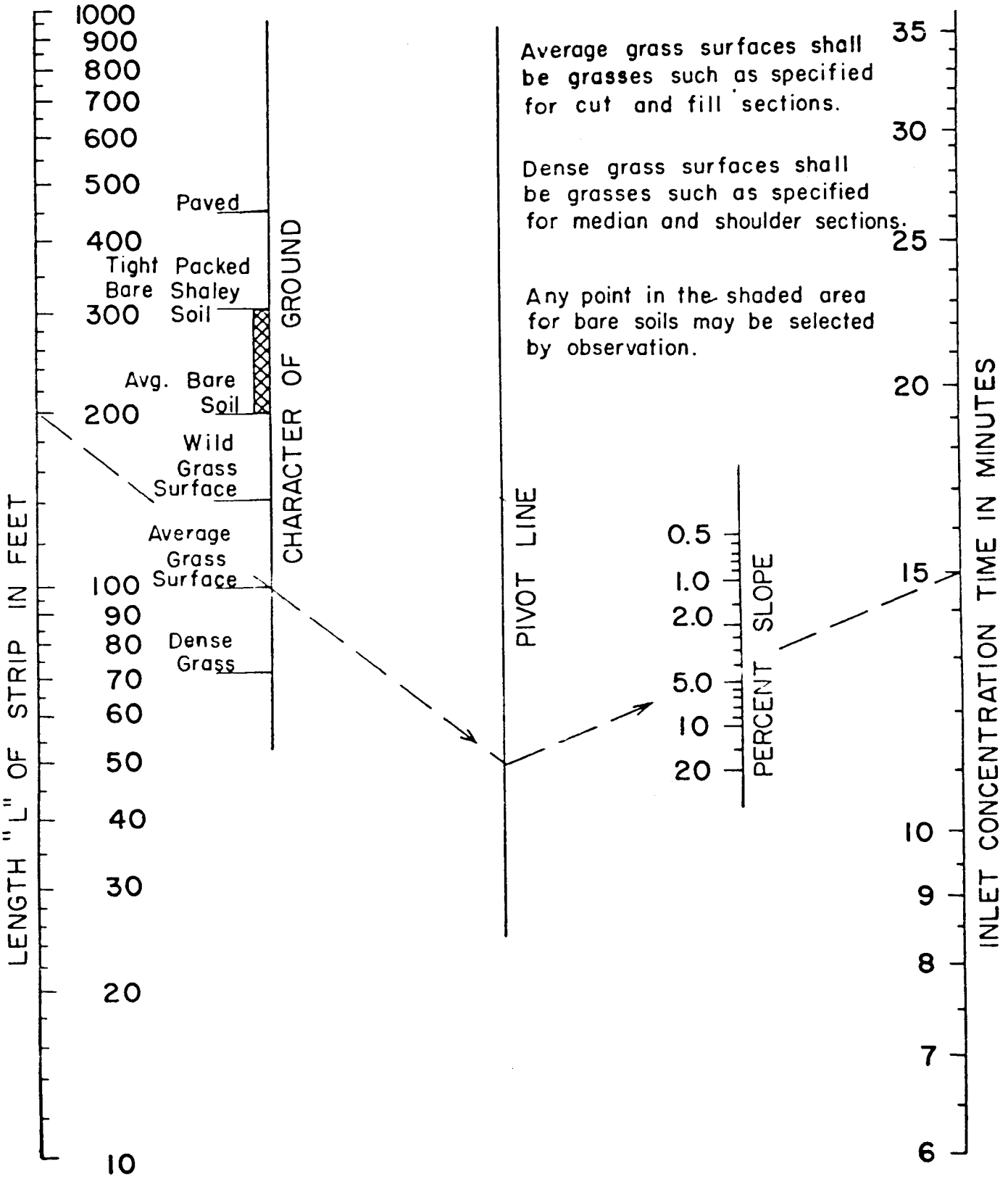
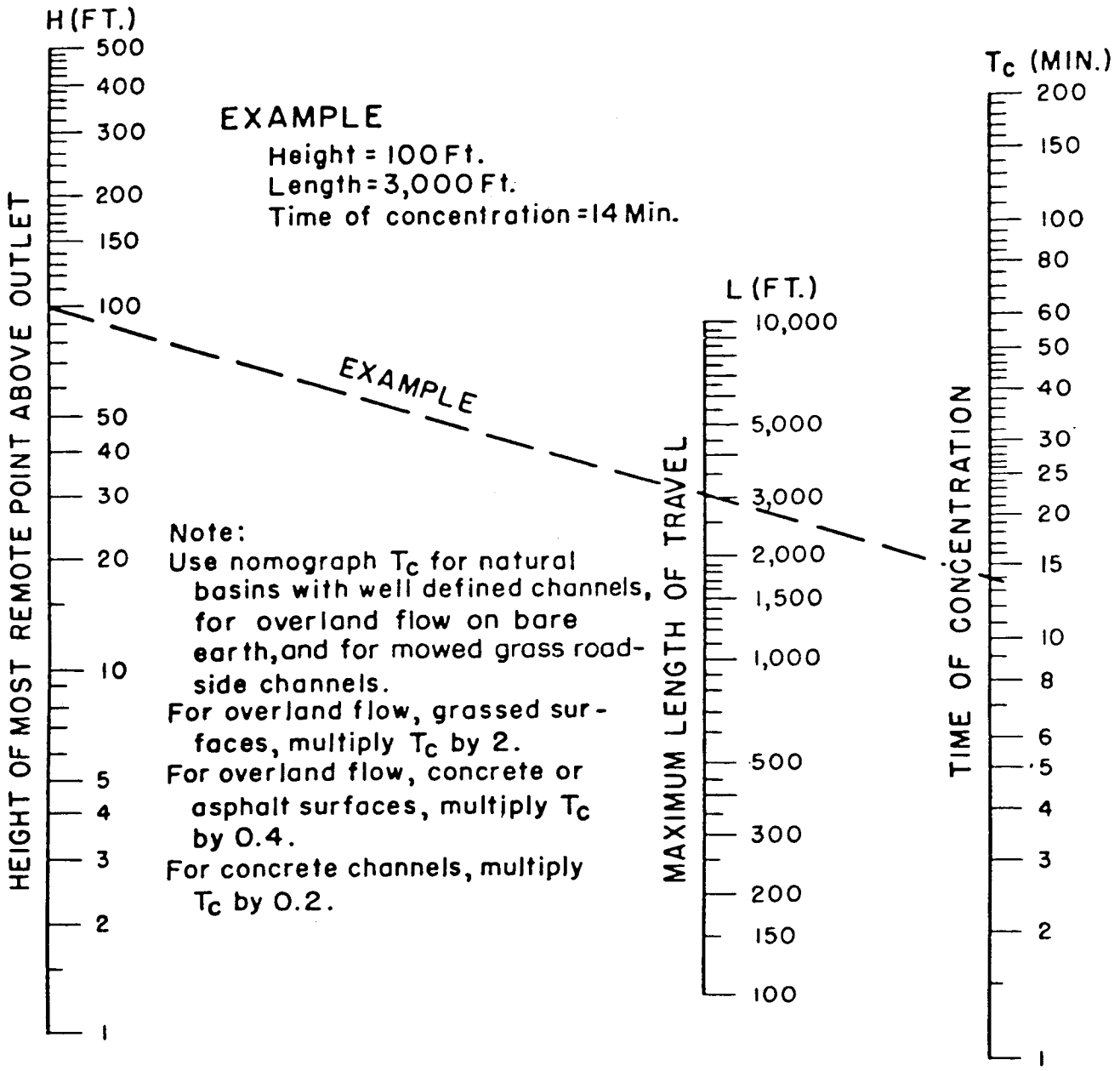


Figure 3.1. Nomograph for computing t_c (from West Virginia Department of Highways).



Based on study by P. Z. Kirpich,
Civil Engineering, Vol. 10, No. 6, June 1940, p. 362

Figure 3.2. Time of concentration of small rural drainage basins (from West Virginia Department of Highways).

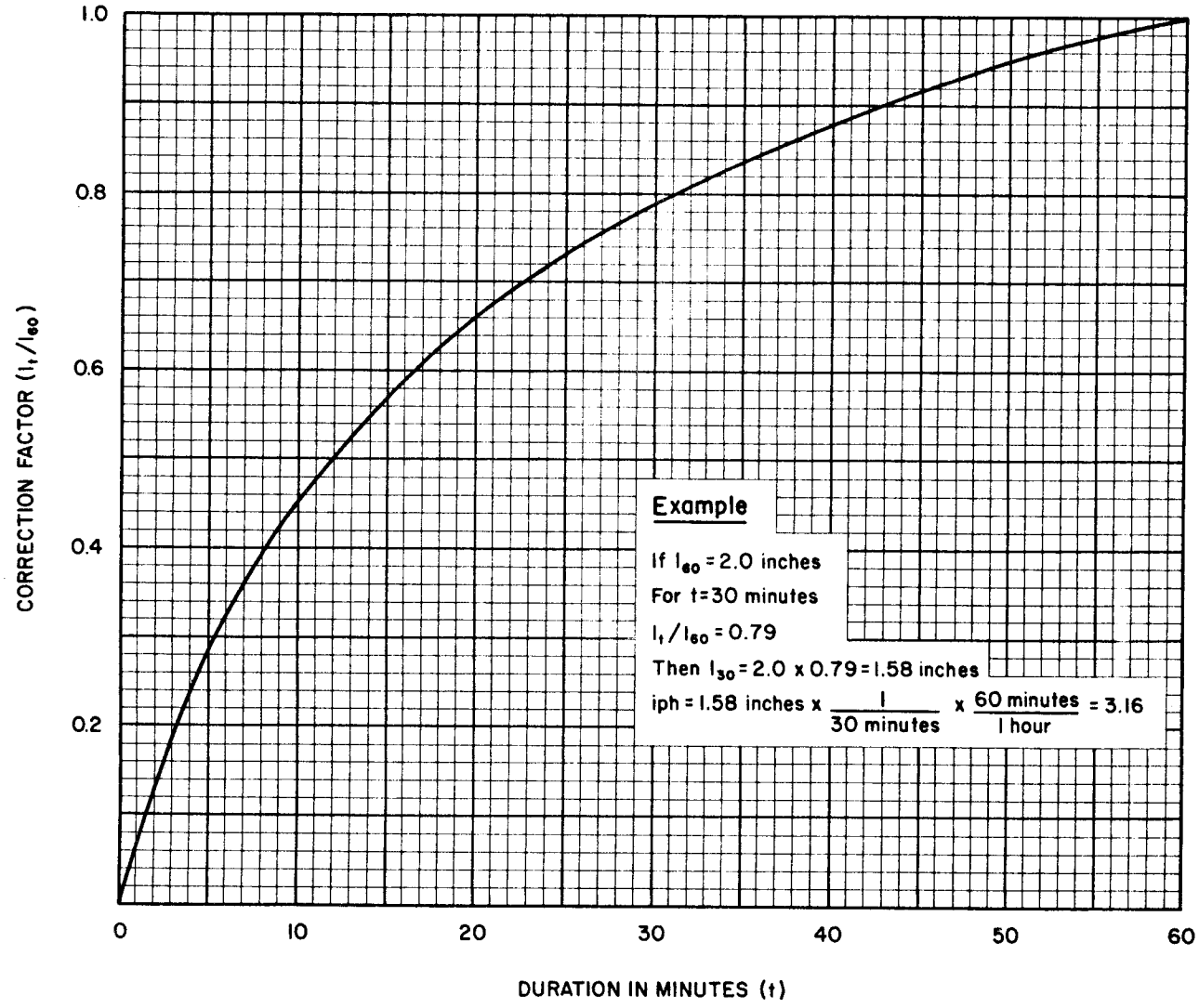


Figure 3.3. Conversion factors for durations less than one hour.

Table 3.3. Rational Runoff Coefficients (after Schwab et al., 1971).

Topography and Vegetation	Values of C in Q = CiA — Soil Texture: Open Sandy Loam	Clay and Silt Loam	Tight Clay
Woodland			
Flat 0-5% slope	0.10	0.30	0.40
Rolling 5-10% slope	0.25	0.35	0.50
Hilly 10-30% slope*	0.30	0.50	0.60
Pasture			
Flat	0.10	0.30	0.40
Rolling	0.16	0.36	0.55
Hilly	0.22	0.42	0.60
Cultivated			
Flat	0.30	0.50	0.60
Rolling	0.40	0.60	0.70
Hilly	0.52	0.72	0.82

*Values are not available for steeper slope conditions, so when applying the Rational Formula to steeper slopes this limitation must be realized.

Considerable care should be exercised in using the tabulated values to insure reasonable results. From a review of the table it is apparent that vegetation has a considerable influence on the peak runoff rate. A surface mine operation will, at least temporarily, change a substantial portion of the drainage basin vegetation type, for example from woodland to cultivated (disturbed). Therefore, a weighted C value will most often be required. Additionally, the designer must realize that the most critical period of channel stability is immediately after regrading, before the vegetation has become established. Not only are potential erosion rates the greatest, but also the peak runoff rate due to the lack of resistance to overland flow. Since there can be no assurance of when the design storm will occur, the designer may want to assume the worst condition to prevent potential failure of the drainagae system.

3.3 SCS TP-149 Method

Discrepancies between some of the commonly used methods of peak rate estimation under similar conditions prompted the SCS to develop the method presented in SCS TP-149 (Kent, 1968). The primary differences in results between the methods (i.e., Rational formula, Cook's Method, etc.) were due to the choice of coefficients and factors inherent in each method rather than to the method itself.

The development of the TP-149 method was based on the need to produce a reliable procedure for making quick, on-the-spot estimates of peak discharge rates. The method is a simplified graphical approach that is closely allied with the SCS NEH-4 procedure. The graphs were computer generated using average conditions for the various parameters and correction factors involved in NEH-4. Therefore, the peak discharge of a small watershed with unusual characteristics can be more accurately computed using NEH-4 if necessary. Graphs were prepared for two distributions of storm rainfall with time. Type I represents Hawaii, Alaska, and the coastal side of the Sierra Nevada and Cascade Mountains in California, Oregon and Washington. The Type II distribution represents the rest of the United States, Puerto Rico and the Virgin Islands. Therefore, most all surface mining areas in the United States are covered by the Type II graphs.

The graphs have also been prepared for curve numbers (CN) of 60, 65, 70, 75, 80, 85 and 90. Identifying the representative CN requires sound judgment

based upon the specific information. Table 3.4 provides the association of CN's with various hydrologic soil-cover complexes for average antecedent moisture conditions (AMC II). Soils are divided into four hydrologic soil groups: A, B, C and D. The groups are included in NEH-4 (Soil Conservation Service, 1972). Group A soils have a high infiltration rate even when thoroughly wet. When thoroughly wet, group B soils have a moderate infiltration rate, group C soils have a slow infiltration rate, and group D soils have a very slow infiltration rate. Typically, most soils in the Eastern Coal Province are in the Type C group. Table 3.5 describes the properties of the four soil group classifications. NEH-4 lists more than 4000 soils and their hydrologic group classifications. For greater detail or accuracy in defining the CN, refer to NEH-4.

The graphs also involve average watershed slope as defined by flat, moderate or steep. Table 3.6 gives the values assumed in the computer generated graphs for TP-149 and the slope ranges assigned to each slope factor. If a closer estimate of peak discharge is required for a specific slope, curvilinear interpolation can be used between 1, 4 and 16 percent. Ordinarily the peak discharge values for one of the three slope categories will be adequate without interpolating between slope categories.

The method is generally limited to drainages less than 2000 acres and average slopes less than 30 percent. For watersheds exceeding these limits SCS recommends that the methods in NEH-4 be followed (Kent, 1968). Additionally, since the graphs were developed for typical or average conditions, a watershed with unusual characteristics should be evaluated by NEH-4. However, as previously mentioned, the method probably yields reasonable results for design in surface mine situations. Appendix B provides the required graphs for Type II rainfall distribution.

3.4 Calculation Procedures

3.4.1 Rational Formula

1. Estimate runoff coefficient C or an area-weighted C, from Table 3.3.
2. Evaluate the time of concentration t_c (min) from Table 3.2, Figure 3.1 or Figure 3.2, depending on available data.
3. Determine the rainfall intensity i (iph) for a duration equal to t_c. If t_c is less than one hour, obtain the one-hour rainfall amount for the design return period from the charts in Appendix A. Then evaluate

Table 3.4. Runoff Curve Numbers for Hydrologic Soil-Cover Complexes. [Antecedent Moisture Condition (AMC) II and $I_a = 0.25$]

Land Use and Treatment or Practice	Hydrologic Condition	Hydrologic Soil Group A	B	C	D
Fallow					
Straight row	----	77	86	91	94
Row crops					
Straight row	Poor	72	81	88	91
Straight row	Good	67	78	85	89
Contoured	Poor	70	79	84	88
Contoured	Good	65	75	82	86
Contoured and terraced	poor	66	74	80	82
Contoured and terraced	Good	62	71	78	81
Small grain					
Straight row	Poor	65	76	84	88
Straight row	Good	63	75	83	87
Contoured	poor	63	74	82	85
Contoured	Good	61	73	81	84
Contoured and terraced	Poor	61	72	79	82
Contoured and terraced	Good	59	70	78	81
Close-seeded legumes or rotation meadow					
Straight row	Poor	66	77	85	89
Straight row	Good	58	72	81	85
Contoured	Poor	64	75	83	85
Contoured	Good	55	69	78	83
Contoured and terraced	Poor	63	73	80	83
Contoured and terraced	Good	51	67	76	80
Pasture or range					
No mechanical treatment	Poor	68	79	86	89
No mechanical treatment	Fair	49	69	79	84
No mechanical treatment	Good	39	61	74	80
Contoured	Poor	47	67	81	88
Contoured	Fair	25	59	75	83
Contoured	Good	6	35	70	79
Meadow	Good	30	58	71	78
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	25	55	70	77
Farmsteads	----	59	74	82	86
Roads[1]					
Dirt	----	72	82	87	89
Hard surface	----	74	84	90	92

[1] Including rights of way.

Table 3.5. Soil Conservation Service Soil Group Classifications.

Soil Group	Description
A	Lowest Runoff Potential. Includes deep sands with very little silt and clay, also deep, rapidly permeable loess.
B	Moderately Low Runoff Potential. Mostly sandy soils less deep than A, and loess less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting.
C	Moderately High Runoff Potential. Comprises shallow soils and soils containing considerable clay and colloids, though less than those of Group D. The group has below-average infiltration after presaturation.
D	Highest Runoff Potential. Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeably subhorizons near the surface.

From U.S. Soil Conservation Service, National Engineering Handbook, Hydrology, Section 4, Part I, Watershed Planning (1964).

Table 3.6. Slope Factors for Peak Discharge Computations in the TP-149 Method.

Slope Factor	Slope for Which Computations Were Made (%)	Average Slope Range (%)
Flat[1]	1	0 to 3
Moderate	4	3 to 8
Steep	16	8 or more

[1] Level to nearly level.

the required correction factor from Figure 3.3 to obtain the rainfall amount for the t_c. The intensity i required in the Rational Formula is then

$$iph = t_c \text{ rainfall amount (in)} \times \frac{1}{t_c \text{ (min)}} \times \frac{60 \text{ min}}{1 \text{ hr}}$$

If t_c is greater than one hour, obtain the one- and 24-hour rainfall amounts for the design return period and evaluate the amount for t_c by interpolation on semilog paper. Compute the iph as described above.

4. Establish the contributing drainage area A (acres).
5. Evaluate $Q = CiA$ (cfs).

3.4.2 SCS TP-149 Method

1. Estimate the curve number (CN) from Table 3.4.
2. Determine the 24-hour duration rainfall for the required return period from the charts in Appendix A.
3. Enter the appropriate chart in Appendix B to determine Q in cfs.

3.5 Example Using Step-By-Step Procedures Outlined Above

From a topographic map the drainage area is estimated as 70 acres and the maximum flow length is 2750 ft. The terrain is hilly with an average 20 percent slope and consists primarily of woodland with a clay and silt loam soil. What is the discharge for the ten-year event near Charleston, West Virginia?

3.5.1 Rational Formula

1. From Table 3.3 $C = 0.50$.
2. From formula given in Table 3.2,

$$t_c = 0.0078\ (2750)^{0.77}\ (0.20)^{-0.385}$$

$$t_c = 6.5 \text{ min.}$$

3. From Appendix A the rainfall amount for the ten-year, one-hour event is 2.0 inches. From Figure 3.3 the correction factor for duration equal to 6.5 minutes is 0.30.

$$I_{6.5} = 2.0\ (0.30) = 0.60 \text{ inches}$$

$$\text{iph} = 0.60 \text{ inches} \times \frac{1}{6.5 \text{ min}} \times \frac{60 \text{ min}}{1 \text{ hour}} = 5.5 \text{ iph}$$

4. Contributing area given as 70 acres.
5. From $Q = CiA$

$$= 0.50\ (5.5)\ (70)$$

$$Q_p = 192 \text{ cfs}$$

3.5.2 SCS TP-149 Method

1. For group C soils, the CN from Table 3.4 is 73 for woods in fair condition.
2. From Appendix A, the ten-year, 24-hour event is 4.2 inches.
3. From charts in Appendix B,

for CN = 70 Q_p = 90 cfs

CN = 75 Q_p = 130 cfs

By linear interpolation, CN = 73 Q_p = 114 cfs.

3.6 References

Kent, K. M., 1968, "A Method for Estimating Volume and Rate of Runoff in Small Watersheds," USDA SCS TP-149, January.

Kirpich, P. Z., 1940, "Time of Concentration of Small Agricultural Watersheds," Civil Engineering, 10.

McPherson, M. B., 1969, "Some Notes in the National Method of Storm Drainage Design," Technical Memorandum No. 6, ASCE Urban Water Resources Program, ASCE.

Schwab, G. O., R. K. Frevert, T. W. Edminster, K. K. Barnes, 1966. Soil and Water Conservation Engineering, John Wiley and Sons, Inc., New York.

U.S. Weather Bureau, 1961, "Rainfall Frequency Atlas of the United States," Technical Paper No. 40, May.

U.S. Soil Conservatin Service, 1964, "Hydrology," National Engineering Handbook, Section 4, Part I, Watershed Planning.

U.S. Soil Conservation Service, 1972, "Hydrology," National Engineering Handbook, Section 4, August.

West Virginia Department of Highways, 1963, Drainage Manual, developed by the Design Division, June.

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