Appendix A-1: Runoff Peak Discharge Calculations

Rational Method - ASCE, 1992 and Rossmiller, 1980

Applicability: The Rational Method establishes an empirical formula that is commonly used in urban areas for computing peak rates of runoff for designing drainage structures. It is useful in estimating runoff on relatively small areas such as roof tops and parking lots. Use of the rational equation should be limited to drainage areas less than 20 acres (Amer. Public Works Assn., 1974) with generally uniform cover type and grade. Required output = peak discharge only. Drainage area < 20 acres.

Description of Method: The Rational Method is used for determining peak discharges from small drainage areas. This method is traditionally used to size storm sewers, channels, and other stormwater structures which handle runoff from drainage areas less than 20 acres. The Rational Formula is expressed as Q = CiA where:
Q =Peak rate of runoff in cubic feet per second
C =Runoff coefficient, an empirical coefficient representing a relationship between rainfall and runoff.
i =Average intensity of rainfall in inches per hour for the time of concentration (Tc) for a selected frequency of occurrence or return period.
A =The watershed area in acres
Tc =The rainfall intensity averaging time in minutes, usually referred to as the time of concentration, equal to the time required for water to flow from the hydraulically most distant point in the watershed to the point of design.

The general procedure for determining peak discharge with the Rational Formula is:

Step 1 Determine the drainage area.

Step 2 Determine the runoff coefficient, C, for the type of soil/cover in the drainage area. If land use and soil cover are homogeneous over the drainage area, a C value can be determined from the following tables. If there are multiple soil cover conditions, a weighted average must be performed.

Step 3 Determine the rainfall intensity averaging time, Tc, in minutes for the drainage area (time required for water to flow from the hydraulically most distant point of that tributary watershed which produces the greatest discharge to the point of design).

Step 4 *D*etermine the Rainfall Intensity Factor, i, for the selected design storm. This is done by using the Rainfall Intensity - Frequency - Duration charts (http://precip.eas.cornell.edu/). These hydrologic charts should be used for the location to be evaluated as they are continuously updated with every new rain event and considered to be most accurate than any other source. Select the chart for the locality closest to the project site. Enter the "Duration" axis of the chart with the calculated time of concentration, Tc. Move vertically until you intersect the curve of the appropriate design storm; then move horizontally to read the Rainfall Intensity Factor, i, in inches per hour.

Step 5 Determine the peak discharge (Q - in cubic feet per second) from equation above.

Assumptions: The peak rate of runoff at any point is a direct function of the tributary drainage area and the average rainfall intensity during the time of concentration to that point based on the following:
- The return period of the peak discharge rate is the same as the return period of the average rainfall intensity or rainfall event. While watershed-related variations such as antecedent moisture conditions may cause this relationship to break down, this assumption is widely used in methodologies for estimating peak flows or hydrographs.
- The rainfall is uniformly distributed over the watershed. Whether this assumption is true depends upon the size of the watershed and the rainfall event.

- The rainfall intensity remains constant during the time period equal to Tc. Based on rainfall records, this assumption is true for short periods of time (a few minutes), but becomes less true as time increases. In turn, this assumption has led to a common misconception that the duration of the storm is equal to Tc. This is theoretically possible but it is much more common for the total storm duration to be considerably longer than Tc. Of equal importance is the concept that Tc (the rainfall intensity averaging time) can occur during any segment of the total storm duration; at the beginning, before, during or after the middle portion; or near the end. This concept has important implications for the runoff coefficient C and how well the Rational Formula mirrors the hydrologic cycle. If an intensity for a duration that is equal to or slightly greater than Tc occurs at the beginning of the storm, then the antecedent moisture conditions become important. If Tc occurs near the end of a long storm, then the ground may be saturated and depression storage already filled when Tc begins.
- The relationship between rainfall and runoff is linear. If rainfall is doubled then runoff is doubled. This is not accurate because of all the variables which interact and determine runoff. In fact, one of the major misconceptions on the use of the formula is that each of the variables (C, i, A) is independent and estimated separately. In reality, there is some interdependency among variables; however, the aids used in estimating the variables do not recognize such a relationship.
- The runoff coefficient, C, is constant for storms of any duration or frequency on the watershed. This is a major misconception of many who use the Rational Formula. C is a variable and during the design of a stormwater system, especially a storm sewer, it should take on several different values for the various segments even though the land use remains the same.

Limitations: The Rational Formula only produces one point on the runoff hydrograph, the peak discharge rate. Where a hydrograph is required, other methods must be used.

- When basins become complex, and where sub-basins combine, the Rational Formula will tend to overestimate the actual flow. The overestimation will result in the oversizing of stormwater management systems. For this reason, the formula should not be used for larger developments as a basis for establishing predevelopment flow rates, which are used to define the restrictions needed for peak rate control.
- The artificially high estimates could result in release rates higher than existing conditions, resulting in adverse effects downstream.
- The method assumes that the rainfall intensity is uniform over the entire watershed. This assumption is true only for small watersheds and time periods, thus limiting the use of the formula to small watersheds.
- The results of using the formula are frequently not replicable from user to user. There are considerable variations in interpretation and methodology in the use of the formula. The simplistic approach of the formula permits, and in fact, requires a wide latitude of subjective judgment in its application.
- Average rainfall intensities used in the method bear no time sequence relation to the actual rainfall pattern during a storm. The intensity-duration-frequency curves prepared by the Weather Bureau are not time sequence curves of precipitation. The maxima of the several durations as used in the method are not necessarily in their original sequential order; and the resulting tabulations of maxima ordered by size or duration may bear little resemblance to the original storm pattern. In many, if not most, cases, the intensities on the same frequency curve for various durations are not from the same storm.

RUNOFF COEFFICIENTS FOR THE RATIONAL FORMULA

Typical Composite Runoff Coefficients by Land Use		Normal Range of Runoff Coefficients	
Area Description	C-value	Surface Characteristic	C-value
Business		**Lawns**	
Downtown Areas	0.70-0.95	Sandy Soil, Flat (2%)	0.05-0.10
Neighborhood Areas	0.50-0.70	Sandy Soil, Ave. (2-7%)	0.10-0.15
		Sandy Soil, Steep (>7%)	0.15-0.20
Residential		Heavy Soil, Flat (2%)	0.13-0.17
Single Family Areas	0.30-0.50	Heavy Soil, Ave. (2-7%)	0.18-0.22
Multi-Units (detached)	0.40-0.60	Heavy Soil, Steep (>7%)	0.2500.35
Multi-Units (attached)	0.60-0.75		
Suburban	0.25-0.40	**Agricultural**	
Apartments	0.50-0.70	Bare Packed Soil	
		Smooth	0.30-0.60
Industrial		Rough	0.20-0.50
Light Use	0.50-0.80	Cultivated Rows	
Heavy Use	0.60-0.90	Heavy Soil, no crop	0.30-0.60
Railroad Yards	0.20-0.35	Heavy Soil, with crop	0.20-0.50
Unimproved Areas	0.10-0.30	Sandy Soil, no crop	0.20-0.40
		Sandy Soil, with crop	0.10-0.25
Park		Pasture	
Park/Cemeteries	0.10-0.25	Heavy Soil	0.15-0.45
Playgrounds	0.20-0.35	Sandy Soil	0.05-0.25
Pavement		**Woodland**	0.05-0.25
Asphalt and Concrete	0.70-0.95		
Brick	0.70-0.85		
Roof	0.75-0.95		

The presented C-values are typical for return periods of 2-10-year storms with the higher values for the larger design storms. Judgement must be used to select the appropriate C-value within the range for the land use. Generally, larger areas with permeable soils, flat slopes, and dense vegetation should have the lower C-value; and smaller areas with low permeability soils, steep slopes and sparse vegetation should be assigned higher a C-value.

RUNOFF COEFFICIENTS FOR THE RATIONAL FORMULA BY HYDROLOGIC SOIL GROUP AND SLOPE

Land Use	A			B			C			D		
	0-2%	2-6%	6+%	0-2%	2-6%	6+%	0-2%	2-6%	6+%	0-2%	2-6%	6+%
First row of each entry provides runoff coefficients for storm recurrence intervals of 25 years or less. Second row provides runoff coefficients for storm recurrence intervals of 25 years or more.												
Cultivated Land	0.08	0.13	0.16	0.11	0.15	0.21	0.14	0.19	0.26	0.18	0.23	0.31
	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Pasture	0.12	0.20	0.30	0.18	0.28	0.37	0.24	0.34	0.44	0.30	0.40	0.50
	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Meadow	0.10	0.16	0.25	0.14	0.22	0.30	0.20	0.28	0.36	0.24	0.30	0.40
	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Forest	0.05	0.08	0.11	0.08	0.11	0.14	0.10	0.13	0.16	0.12	0.16	0.20
	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Residential												
Lot Size (1/8 acre)	0.25	0.28	0.31	0.27	0.30	0.35	0.30	0.33	0.38	0.33	0.36	0.42
	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Lot Size (1/4 acre)	0.22	0.26	0.29	0.24	0.29	0.33	0.27	0.31	0.36	0.30	0.34	0.40
	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Lot Size (1/3 acre)	0.19	0.23	0.26	0.22	0.26	0.30	0.25	0.29	0.34	0.28	0.32	0.39
	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Lot Size (1/2 acre)	0.16	0.20	0.24	0.19	0.23	0.28	0.22	0.27	0.32	0.26	0.30	0.37
	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.48
Lot Size (1 acre)	0.14	0.19	0.22	0.17	0.21	0.26	0.20	0.25	0.31	0.24	0.29	0.35
	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Industrial	0.67	0.68	0.68	0.68	0.68	0.69	0.68	0.69	0.69	0.69	0.69	0.70
	0.85	0.85	0.85	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.71	0.71	0.71	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets	0.70	0.71	0.71	0.71	0.72	0.74	0.72	0.73	0.76	0.73	0.75	0.78
	0.76	0.77	0.80	0.80	0.82	0.84	0.84	0.85	0.80	0.89	0.91	0.95
Open Space	0.05	0.10	0.08	0.08	0.13	0.19	0.12	0.17	0.24	0.16	0.21	0.28
	0.11	0.16	0.14	0.14	0.19	0.26	0.18	0.23	0.32	0.22	0.27	0.39
Parking	0.85	0.86	0.85	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87
	0.95	0.96	0.95	0.95	0.96	0.97	0.95	0.95	0.97	0.95	0.96	0.97

Appendix A-2: Runoff Peak and Volume Calculations

SCS TR-55 Graphical Method - Soil Conservation Service, 1986

Applicability: Determines peak runoff, the runoff volume, and the time to peak for a single homogeneous sub-area or watershed only for drainage areas up to 2000 acres. This method is recommended for use in the design of erosion and sediment control measures. When more detail and accuracy is required or when an accurate simulation of natural conditions is required, one of the other appropriate methods should be used.

Description of Method: The Graphical Method was developed from hydrograph analyses using TR-20. It provides a simplified approach to estimating peak runoff and total runoff volumes while accounting for slope, soils, and watershed shape. Refer to TR-55 for a detailed description of the use of the method.

Limitations: Refer to applicable chapters of TR-55 for specific limitations, including those pertaining to the derivation of Curve Number (CN) and Time of Concentration (Tc).

- TR-55 is based on open and unconfined flow over land or in channels. For large events during which flow is divided between sewer and overland flow, more information about hydraulics is needed to determine Tc. After flow enters a closed system, the discharge can be assumed constant until another flow is encountered at a junction or another inlet.
- The Graphical Peak Discharge method is derived from TR-20 (SCS 1983) output. The use of Tc permits it to be used for any size watershed within the scope of the curves or tables. The Graphical method is used only for hydrologically homogeneous watersheds because the procedure is limited to a single watershed subarea.
- The Graphical method provides a determination of peak discharge only. If a hydrograph is needed or watershed subdivision is required, use the Tabular Hydrograph method. Use TR-20 if the watershed is very complex or a higher degree of accuracy is required.
- The watershed must be hydrologically homogeneous, that is, describable by one CN. Land use, soils, and cover are distributed uniformly throughout the watershed.
- The watershed may have only one main stream or, if more than one, the branches must have nearly equal Tc's.
- The method cannot perform valley or reservoir routing.
- The ponding factor can be applied only for ponds or swamps that are not in the Tc flow path.
- Accuracy of peak discharge estimated by this method will be reduced if Ia/P values are used that are outside the range given in the TR-55 reference. The limiting Ia/P values are recommended for use.
- This method should be used only if the weighted CN is greater than 40.
- When this method is used to develop estimates of peak discharge for both present and developed conditions of a watershed, use the same procedure for estimating Tc.
- Tc values with this method may range from 0.1 to 10 hours.

Appendix A-3: Other Methods and Models

SCS TR-20 - Soil Conservation Service, 1983

Applicable for drainage areas up to 20 square miles, the TR-20 hydrologic model is used for watershed analysis where any of the following conditions are applicable.

- Sub-areas are significantly different in size (5:1), land use (cover), or hydrologic soil groups.
- An outflow hydrograph from a detention pond is needed.
- A detention basin has multiple sub-areas in its drainage area, requiring an accurate peak discharge value and a composite runoff volume.
- Multiple detention structures are used either in parallel or in series.
- Conveyance channel storage is large.
- Calibration of the model using actual rainfall amounts and distribution is needed.
- Flow (splitting) diversions are required

SCS TR-20 Hydrologic Model is a watershed computer model which uses the SCS Synthetic Unit Hydrograph to calculate runoff from any specified precipitation event. SCS TR-20 performs reservoir routing using the storage-indication method and channel routing using the Modified Att-Kin method. Time of concentration, travel time and antecedent moisture conditions are taken into account. The program provides hydrographs at any desired location allowing the evaluation of the effects of urbanization or other varied conditions within a watershed. The program allows for the analysis of nine different rainstorm distributions over a watershed and can utilize varied combinations of land treatment, floodwater retarding structures, diversions and channel configurations. Up to 200 reaches and 99 structures may be analyzed. The model can be used in design or watershed simulation. It is normally calibrated to actual events for large projects.

This procedure should be used with caution for drainage areas less than 50 acres or individual drainage areas more than 20 square miles. It may be used on watersheds up to 391 square miles in area, assuming subdivision of the total watershed into relatively homogeneous sub-watersheds of less than 20 square miles each, and routing through all subareas to the study point.

SCS TR-55 Tabular Method - Soil Conservation Service, 1986

For drainage areas up to 2,000 acres, the Tabular Method approximates TR-20 which is a more detailed hydrograph procedure; TR-55 is in fact derived from a simplification of the TR-20 model. The Tabular Method can develop composite flood hydrographs at any point in a watershed by dividing the watershed into homogeneous subareas. In this manner, the method can estimate runoff from non-homogeneous watersheds. The method is especially applicable for estimating the effects of land use change in a portion of a watershed. It can also be used to estimate the effects of proposed structures. Refer to TR-55 for a detailed description of the use of the method.

Refer to applicable chapters of TR-55 for specific limitations, including those pertaining to the derivation of Curve Number (CN) and Time of Concentration (Tc).

- TR-55 is based on open and unconfined flow over land or in channels. For large events during which flow is divided between piped or channelized and overland flow, more information about hydraulics is needed to determine Tc. After flow enters a closed system, the discharge can be assumed constant until another flow is encountered at a junction or another inlet.
- The Tabular Hydrograph method is derived from TR-20 output. The use of Tc permits it to be used for any size watershed within the scope of the curves or tables. The Tabular Method can be used for a heterogeneous watershed that is divided into a number of homogeneous sub-watersheds. Hydrographs for the sub-watersheds can be routed and added.

- The Tabular Method is used to determine peak flows and hydrographs within a watershed. However, its accuracy decreases as the complexity of the watershed increases. To compare present and developed conditions of a watershed, use the same procedure for estimating Tc for both conditions.
- Use the TR-20 computer program instead of the Tabular Method if any of the following conditions applies:
    - Tt is greater than 3 hours.
    - Tc is greater than 2 hours.
    - Drainage areas of individual subareas differ by a factor of 5 or more.
    - The entire composite flood hydrograph or entire runoff volume is required for detailed flood routings. The hydrograph based on extrapolation is only an approximation of the entire hydrograph.
    - The time of peak discharge must be more accurate than that obtained through the Tabular Method.
    - CN is less than 30.
- The composite flood hydrograph should be compared with actual stream gage data where possible. The instantaneous peak flow value from the composite flood hydrograph can be compared with data from USGS curves of peak flow versus drainage area.

Corps of Engineers: HEC-1- Hydrologic Engineering Center, 1990

Same as TR-20, but in addition considers snowmelt behavior. It can be used in reverse to determine a unit hydrograph given watershed parameters and an actual rainfall and hydrograph event. HEC-1 requires the input of more complex data than TR-20, but provides greater flexibility in calibrating a rainfall runoff model with actual stream gauge records. The program develops discharge hydrographs for either historical or hypothetical events for one or more locations in a watershed that can be subdivided into many subwatersheds. Reservoirs and diversions can also be accommodated. The program options include: calibration of unit hydrograph and loss-rate parameters, calibration of routing parameters, generation of hypothetical storm data, simulation of snow pack processes and snow melt runoff, dam safety applications, multi-plan/multi-flood analysis, flood damage analysis, and optimization of flood control system components. A disadvantage could exist in small rugged watersheds where actual runoff documentation is not available. In an area where all soils have been mapped by SCS, the SCS runoff curve number method may offer more accurate results.

USGS Regression Equations (for Maine) - USGS, 1975

The method gives peak discharges for unregulated watersheds in Maine for the 2, 5, 10, 25, 50, 100 and 500 year peak discharge flows for drainage areas from 200 acres and greater. It does not give runoff volumes or hydrographs. This method may be used for structures needing only a peak discharge for design. It can also be used to calibrate or "ground truth" the TR-20 model. The gage network of data analyzed did not include urban (developed) watersheds with a high percent of imperviousness. The USGS method requires the following data as inputs:

- Drainage area (square miles)
- Channel length (miles)
- Mean sea level (MSL) elevation at 85% of length at the upper end and 10% of length at lower end.
- Pond and lake area in watershed (sq. miles).
- The watershed being studied must be unregulated (no dams, etc.), not heavily urbanized, and of a configuration common to watersheds in the database used.
- Before and after comparisons are not possible. The method's records include changing land use patterns, and records do not exist for long enough to do separate analysis of past and present land use and peak values.

Soil Conservation Service NEH-4 - Soil Conservation Service, 1972.

National Engineering Handbook Section 4 provides watershed analysis using the SCS Unit

Hydrograph Method. Runoff hydrographs are calculated for a preselected rainfall distribution or duration, either natural or synthetic. Either peak discharge or a composite runoff hydrograph can be developed for watersheds of any size. This reference, primarily intended for SCS engineers and technicians, also contains methods and examples for studying the hydrology of watersheds and solving hydrologic problems.

Source Loading and Management Model - (SLAMM)

This model is designed for calculating urban runoff water quality, and does not contain the assumptions that affect runoff predictions for small storm events. The model enables close examination of individual source areas and their resulting impact on overall pollutant load if they are controlled or removed from the total study area. SLAMM only calculates runoff volume for water quality studies and does not calculate peak flow rate or time of concentration as typically needed for flooding and drainage studies.

The model is based on the fact that the majority of rainfall is contained in small rains (less than one inch) where other models, such as TR-55, do not correlate well with actual precipitation and runoff data for these smaller storms. SLAMM predicts runoff volumes and runoff pollutant yield (or reduction) estimates for the watershed for variable land uses and stormwater controls.