Using the Rational Method to Determine Peak Flow

Design Manual
Chapter 4
Drainage
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This section addresses the following:

- The Rational Method. Note: the Rational Method cannot be used for drainage basins greater than 160 acres.
  - The Rational equation.
  - Drainage area (A).
  - Runoff coefficient (C).
    - Table of runoff coefficients for the Rational Method.
    - Determining a composite C.
  - Rainfall intensity (I).
    - Recurrence interval (frequency).
    - Time of concentration.
      - Overland sheet flow.
      - Shallow concentrated flow.
      - Open channel flow.
- Calculating peak flow (Q) for a drainage area.
- Design application.

Designers need to be aware of work being done by the other offices for the same project site and coordinate with them to determine the design effort required by each office.

The Rational Method

CADD: GEOPAK Drainage can help with the Rational Method calculations. See Section 4A-54, GEOPAK Drainage-Area for instructions.

For most roadway stormwater drainage systems, the Rational Method can be used to determine peak flow (Q). If drainage areas involve pump stations or include topography or structures that retain or detain water, the Rational Method cannot be used. Use other nationally accepted methods.

The Rational Method is limited to drainage basins 160 acres or smaller. This is a result of the assumptions associated with the Rational Method, which include:

- Recurrence interval (T_R) used for estimating peak flow is the same as that for determining rainfall intensity (i.e., a 50 year storm is assumed to produce a 50 year peak flow). Peak flow is assumed to occur when the entire watershed is contributing to flow.
- Rainfall intensity is the same over the entire drainage area and is uniform over a time duration equal to the time of concentration (T_c).

For drainage areas larger than 160 acres, other methods of determining peak flow (for example, the SCS (NCRS) peak flow method) are required. These are discussed in HEC-22.

The Rational Equation

The Rational Method uses the Rational equation given below:

$$Q = CIA \quad \text{(Equation 4A-5\_1)}$$

where:

Q = Peak flow, ft^3/s.

C = Runoff coefficient (dimensionless).

I = Rainfall intensity, in/hr.

A = Drainage area, acres.

Drainage Area (A)

A drainage basin, or watershed, consists of all drainage areas that contribute flow to an outlet. A drainage basin may consist of one or several drainage areas.

For stormwater system design, a drainage area (A) is the combined area of all surfaces that drain to a given location such as a swale, intake or culvert inlet, pond, stream, etc. Following are some questions to investigate when evaluating a drainage area. Local maintenance authorities may be able to provide information. Documentation of the investigation is important:

- How are individual lots graded? Rear to front? Half to the rear and the other half to the front?
- Will existing contour lines remain the same, or are there known intentions for the area be regraded?
- Which direction will water flow down the gutters of the streets?
- At intersections, what direction will bypass flow or ponded flow go; will water flow around the corner or flow across the intersection?
- Will water run the same direction for all design rainfall intensities? Does bypass flow drain to the same downstream location as the underground storm sewer pipe?
- Are there known or expected roof drains, tile drains, subdrains, sump pumps, or other items that drain to the system? Are some of these draining water from other drainage basins?

Quick Tip: Make a preliminary proposed DTM (TIN) file using survey and photogrammetry information to draw drainage areas. Refer to Sections 40A-5 and 40A-6.

Section 4A-2 lists sources that may be useful when examining drainage areas.

Runoff Coefficient (C)

The runoff coefficient (C), also called the “coefficient of imperviousness,” is the ratio of runoff to rainfall. Factors that contribute to C include:

- Shape of the drainage area.
- Slope of the watershed.
- Land use (percentage of impervious surface and surface type).
- Character of the soil.
- Basin storage potential (potholes, roof storage, etc.).
- Previous (antecedent) moisture conditions.
- Interception by vegetation or animal life (e.g. a beaver dam).
- Rainfall duration.
- Rainfall intensity.
- Recurrence interval (rainfall frequency).

Runoff coefficient values for 5 year, 10 year, 50 year, and 100 year recurrence intervals are given in Table 1.

Table 1: Runoff coefficients for the Rational Method.

description of area	runoff coefficient (C)***			
	5 year	10 year	50 year	100 year
Paved Surfaces/Buildings	0.94	0.95	0.98	0.98
Gravel Surfaces, Compacted	0.45	0.50	0.55	0.60
Gravel Surfaces, Loose Graded or Not Compacted	0.35	0.40	0.45	0.50
Industrial Light, 60% Impervious	0.64	0.69	0.79	0.83
Industrial Heavy, 75% Impervious	0.76	0.79	0.86	0.89
Commercial/Business Areas, 85% Impervious	0.81	0.85	0.91	0.92
Residential Row houses/town houses, 65% Impervious	0.66	0.67	0.74	0.76
Residential 1/4 Acre lots, 40% Impervious*	0.48	0.49	0.58	0.62
Residential 1/2 Acre lots, 25% Impervious*	0.36	0.39	0.49	0.54
Residential 1 Acre lots, 20% Impervious*	0.32	0.34	0.46	0.51
Lawn, 0 to 2% slope (flat) **	0.22	0.22	0.30	0.36
Lawn, 2 to 7% slope (average) **	0.24	0.25	0.35	0.40
Lawn, 7% or greater (steep) **	0.26	0.30	0.38	0.45
Parks/Golf Courses/Cemeteries, 8% Impervious	0.21	0.21	0.28	0.34

* Based on Type B soils. Some regions in Iowa have predominant C and D type soils which require larger 'C' values. Appropriate experience is required in selecting appropriate 'C' values. Contact Office of Design Soils Section for further guidance.

** Based on heavy soils and lawn in fair condition. For situations involving sandy soils, contact the Methods Section

*** For higher percent of imperviousness than in the "description of area", developing land with no cover to poor cover, compacted soils, locations of high water table, and/or soils having a slow infiltration rate when thoroughly wetted, these values may be too low. Consult HEC-22, AASHTO Drainage Design Guidelines, or the Methods Section.

If future land use is unknown, the runoff coefficient should be conservatively based.

Occasionally a single C value can adequately describe an entire project or area. Typically, a different C value is required for each inlet and composite C values are often required. When a drainage area is composed of more than one distinct part, use the weighted average equation below to find a composite C.

$$C = \frac{C_1A_1 + C_2A_2 + C_3A_3 ... + ... C_nA_n}{A_1 + A_2 + A_3 ... + ... A_n} \quad \text{(Equation 4A-5\_2)}$$

where:

A_1, A_2, A_3, … A_n = areas of the distinct parts.

C_1 = C value for A_1, C_2 = C value for A_2, etc.

Example Problem 4A-5_1, Determining Composite C

Rainfall Intensity (I)

Rainfall intensity (I) is the average rate of rainfall given in in/hr that occurs over the duration of a storm. Rainfall intensity is required to use the Rational method. To calculate I, the designer must first select a recurrence interval (T_R). Next the designer calculates the time of concentration (T_c). Once T_R and T_c are known, I is determined using Table 2 (for the Rational method, storm duration is the same as T_c). Often, T_c falls between the values in the tables, so I needs to be interpolated.

Table 2: Rainfall Intensities

Rainfall intensity does not account for a rainfall's variable intensity over time or across a basin, or for how much rainfall fell prior to the period in question. Designers should keep these factors in mind, especially for areas prone to flash flooding.

Rainfall intensities in Table 2 have been revised to be based on NOAA's Atlas 14. Intensities have increased rather substantially over the Bulletin 71 values previously used, especially for 5 minute, 10 minute, and 15 minute storm durations – in excess of 20% in some cases. This change could impact projects that are in the design process. The following guidance is suggested:

- If the system is downstream from a future project that will be designed using Atlas 14, strongly consider switching to Atlas 14. This review will need to include the potential impacts to the design as well as impacts the changes may have on the upstream system.
- If the system is upstream from a project that will be designed using Atlas 14, consider switching to Atlas 14 if the project is still early in the design process.
- If the system is upstream from a project designed using Bulletin 71 intensities, stay with Bulletin 71 intensities. Contact the Methods Engineer if a copy those intensities are needed.

If you are uncertain what to do, contact the Methods Engineer.

Recurrence Interval (Frequency)

When designing stormwater drainage systems, designers rely on the recurrence interval (T_R). Recurrence interval is referred to in a number of different ways: frequency, design flood frequency, storm frequency, recurrence frequency, exceedence interval, or return period.

Recurrence interval is based on probability:

$$T_R = \frac{1}{p}$$

where:

T_R = Recurrence Interval in years.

p = Probability of a storm event that equals or exceeds a specified flow occurring in a given year.

Table 3: Recurrence interval and probability.

recurrence interval (frequency) T_R	probability of equaling or exceeding flow (X% chance storm) p
2 year	50%
5 year	20%
10 year	10%
25 year	4%
50 year	2%
100 year	1%

Since T_R is based on probability, a recurrence interval is not the actual interval for which a storm event is expected to occur. Instead, it represents the probability a storm event will occur in any given year. For example, a storm event with a 50 year recurrence interval has a 2% probability of equaling or exceeding a specified flow in any given year. A 50 year storm event may actually occur several times in a 50 year span, several times in one year, or just once in 100 years. When communicating with or relating to the general public, using terms such as "X% Chance Storm Event" may help reduce confusion and concerns.

Designing a stormwater drainage system to handle the worst storm event that could happen would likely be too costly for most situations. On the other hand, designing a system that is overtaxed by even minor storm events can result in flooding that creates safety issues or economic hardships. Since the consequences of flooding in some areas are more severe than in others, desired design T_R values vary for different elements of a system depending on the area drained, area conveying the runoff, and the need to avoid flooding. The selection of the design T_R is based on several factors, which can include safety, economics, policy, or regulatory requirements. The goal is to balance the cost of the system with potential risk and damage costs.

Interstates, Freeways, Expressways, and Primary Highways

Table 4 provides minimum required design T_R values for interstates, freeways, expressways, and primary highways. More stringent requirements (higher design recurrence intervals) may be necessary in areas where encroachment or ponding can result in traffic delays, property damage, or safety concerns.

Table 4: Required minimum design recurrence interval values

situation	design recurrence interval	X% chance storm
flushing velocity	5 year	20%
intake on continuous grade	10 year	10%
intake at a sag point	50 year	2%
major design storm	100 year	1%

Staged Construction or Detour

Recurrence interval design values selected for staged construction and detours depend on traffic counts, speeds, how long the system will be in place, accommodations for overtopping or bypassed flow, and the consequences should the system be overtaxed. Two years is the minimum recurrence interval design value allowed for temporary staged construction.

Local Streets

Recurrence interval design values for local jurisdictions vary throughout the state. Contact the local jurisdiction.

For reconstruction projects involving storm sewer, existing systems should be analyzed and new systems should be sized using current recurrence intervals even if the original system (and other systems tying into it) was sized using a smaller recurrence interval.

In using the Rational equation to determine peak flow for a given T_R (e.g. 10 year), the same T_R must be used when determining C and I. Occasionally the contributing drainage area A is affected by the T_R as well, due to an increased chance of flow bypassing from one watershed to another during large recurrence interval events.

Time of Concentration (T_c)

Time of concentration (T_c) is the time required for water falling on the hydraulically most remote point in a drainage area to flow to the point of interest. Remoteness relates to time rather than distance. Factors affecting T_c include:

- **Surface roughness.** Rough terrain, such as undeveloped areas, impedes flow of runoff more than smooth surfaces such as pavement. This increases T_c.
- **Channel shape and flow patterns.** Channels typically convey runoff more efficiently than flat terrain. This reduces T_c.
- **Slope.** The velocity of runoff increases with increase in slope. This reduces T_c.

Water traveling a short distance across rough, flat terrain may require more time to reach a point of interest than water traveling a longer distance across smooth, steep terrain. Thus, the most hydraulically distant point in a drainage area may not be the point located furthest from the point of interest.

Total T_c may consist of several components and is calculated as follows:

$$T_c = T_{c\ sheet} + T_{c\ shallow} + T_{open\ channel} \quad \text{(Equation 4A-5\_3)}$$

where:

T_c = Total time of concentration, minutes.

$T_{c\ sheet}$ = Time of concentration for overland sheet flow, minutes.

$T_{c\ shallow}$ = Time of concentration for shallow concentrated flow, minutes.

$T_{c\ open\ channel} = T_{c\ gutter} + T_{c\ pipe} + T_{c\ swale}$.

where:

$T_{c\ gutter}$ = Time of concentration for gutter flow, minutes.

$T_{c\ pipe}$ = Time of concentration for pipe flow, minutes.

$T_{c\ swale}$ = Time of concentration for flow in a swale, minutes

When calculating I, use a minimum total T_c of 5 minutes.

The following worksheet will aid with calculating T_c. The components of the worksheet are further explained below.

Time of Concentration Worksheet

Peak discharge is greatly affected by watershed slope and velocity, so reasonable care and calculations are required to estimate slope for each type of flow. Best results are generally obtained when the slope derived is representative of the areas to which it is being applied. Drainage areas may need to be divided into sub-basins of significantly different topographical elements.

Overland Sheet Flow ($T_{c\ sheet}$)

Overland sheet flow is the shallow mass of runoff over plane surfaces (e.g. parking lots, lawns). Overland sheet flow usually occurs over a short distance at the high end of a drainage area. The National Resources Conservation Service (NRCS) recommends limiting overland sheet flow to 100 feet for unpaved areas. This manual follows the recommendation of NRCS. For paved surfaces, the maximum is 300 feet.

$L_{Tc\ sheet}$ = 100 feet maximum for unpaved areas and 300 feet maximum for paved areas.

Use the kinematic wave equation below to estimate T_c for overland sheet flow:

$$T_{c\ sheet} = \frac{K_u}{I^{0.4}}\left(\frac{nL}{\sqrt{S}}\right)^{0.6} \quad \text{(Equation 4A-5\_4)}$$

where:

$T_{c\ sheet}$ = Overland sheet flow travel time, minutes.

K_u = Empirical coefficient equal to 0.933.

n = Manning's roughness coefficient for overland flow (see Table 5), based on very shallow flow depths of up to 0.1 feet.

L = Overland flow path length, ft.

I = Rainfall intensity rate, in/hr.

S = Slope of the overland flow path, ft/ft.

Table 5: Manning's roughness coefficient (n) for overland flow.

surface description	n
Asphalt and concrete: new existing	 0.016 Refer to Table 2 of Section 4A-6
Cement rubble surface	0.024
Fallow (no residue)	0.05
Cultivated soils: residue cover ≤ 20% residue cover > 20% range (natural)	 0.06 0.17 0.13
Grass: short grass prairie (fields) dense grasses (lawns)	 0.15 0.24
Woods: light underbrush dense underbrush	 0.40 0.80

Table 2 will be necessary to calculate $T_{c\ sheet}$. Since both T_c and I are unknowns, a trial and error process is required using the rainfall intensity values in Table 2. This is how it works:

1. Refer to Table 2 to determine which Section code is appropriate. Choose a value from the "duration" column (this serves as $T_{c\ sheet}$) in Table 2 with the corresponding I from the appropriate "recurrence interval" (10 year or 50 year) column.
2. Calculate $T_{c\ sheet}$ by substituting I into Equation 4A-5_4.
3. Compare the selected value of $T_{c\ sheet}$ with the calculated value from Step 2.
   - If the value of $T_{c\ sheet}$ from Step 2 is less than 5 minutes, use $T_{c\ sheet}$ = 5 min.
   - If the selected $T_{c\ sheet}$ is within one minute of $T_{c\ sheet}$ from Step 2, then $T_{c\ sheet}$ equals the selected value.
   - If the selected $T_{c\ sheet}$ is not within one minute of $T_{c\ sheet}$ from Step 2, then select another value for $T_{c\ sheet}$ (try a value close to the calculated $T_{c\ sheet}$). This may require using values of T_{csheet} not in the tables. If this is the case, I will need to be interpolated. This process is demonstrated in the Sheet Flow Example Problem.
4. Repeat Steps 2 and 3 until the selected value for $T_{c\ sheet}$ is within one minute of the calculated $T_{c\ sheet}$.

Example Problem 4A-5_2. Overland Sheet Flow

Shallow Concentrated Flow ($T_{c\ shallow}$)

After a short distance (depending on ground cover, but always less than 100 feet), overland sheet flow starts to concentrate in rills, and then in gullies. This flow is referred to as shallow concentrated flow. The velocity of this flow is estimated using a relationship between velocity and slope. To calculate $T_{c\ shallow}$, first estimate the velocity of flow using the following equation:

$$V = K_u k \sqrt{S} \quad \text{(Equation 4A-5\_5)}$$

where:

V = Velocity of flow, ft/s.

S = Slope, ft/ft.*

k = Intercept coefficient (see Table 6).

K_u = Units conversion factor*, 33.

*HEC-22 bases slope on percent. Units conversion factors in HEC-22 are smaller by a factor of 10.

Table 6: Intercept coefficients for shallow concentrated flow.

land cover/flow regime	k
Forest with heavy ground litter; hay meadow (overland flow)	0.076
Trash fallow or minimum tillage cultivation; contour or strip cropped; woodland (overland flow)	0.152
Short grass pasture (overland flow)	0.213
Cultivated straight row (overland flow)	0.274
Nearly bare and untilled (overland flow)	0.305
Grassed waterway (shallow concentrated flow)	0.457
Unpaved (shallow concentrated flow)	0.491
Paved area (shallow concentrated flow); small upland gullies	0.619

Once velocity has been determined, use the equation below to calculate $T_{c\ shallow}$.

$$T_{c\ shallow} = \frac{L}{60V} \quad \text{(Equation 4A-5\_6)}$$

where:

$T_{c\ shallow}$ = Shallow concentrated flow travel time, minutes.

L = Flow length, ft.

V = Velocity of flow, ft/s.

Example Problem 4A-5_3, Shallow Concentrated Flow

Open Channel Flow

Open channels for roadway stormwater drainage systems consist of drainage swales, pipes flowing partially full, and gutters.

Gutter Flow ($T_{c\ gutter}$)

Flow time for runoff in the gutter is typically small (1 to 2 minutes, or less) compared to the total T_c, and it is often not included. This produces slightly more conservative results for rainfall intensity, which adds in a factor of safety.

For long gutter lengths (several hundred feet), flat gutter slopes (around or less than 0.50%), or low flows (less than 0.50 ft^3/s), gutter flow time may be several minutes and may need to be included in total (T_c). To estimate gutter flow time, first determine the average velocity using one of the equations below:

$$V = \frac{2Q}{T^2 S_x} \quad \text{(Equation 4A-5\_7, uniform cross section)}$$

$$V = \frac{2Q}{T^2 S_x + W^2 (S_W - S_x)} \quad \text{(Equation 4A-5\_7, composite gutter section)}$$

where:

Q = Flow in gutter, ft^3/s.

T = Spread, ft.

W = Width of depressed section, ft.

S_x = Cross slope of pavement, ft/ft.

S_W = Cross slope of depressed gutter section, ft/ft.

After calculating velocity, use Equation 4A-5_6 to determine ($T_{c\ gutter}$).

Pipe Flow ($T_{c\ pipe}$)

Refer to General Information for Pipe Design in Section 4A-10.

Drainage Swales ($T_{c\ swale}$)

Use Manning's equation (Equation 4A-5_8 below) to estimate average flow velocity. The Manning's roughness coefficient 'n' is a function of several parameters including: channel material type, roughness, thickness (such as size of rocks or height of vegetation), flow velocity and flow depth. This coefficient can have a dramatic result in the outcome of the equation. Table 7 provides a brief list of some average 'n' values for consideration in the design process. The designer should have a good understanding of how and when to use this equation and how to evaluate the use of an appropriate 'n' value before proceeding.

$$V = \frac{K_u}{n}\left(\frac{A}{P_{wetted}}\right)^{0.67}\sqrt{S} \quad \text{(Equation 4A-5\_8)}$$

where:

V = Velocity of flow, ft/s.

S = Slope, ft/ft.

n = Manning's roughness coefficient for open channel flow (See Table 7).

K_u = Units conversion factor, 1.49.

A = Cross sectional flow area, ft^2.

P_{wetted} = Wetted perimeter (surface in contact with water), ft.

Table 7: Values of Manning's coefficient (n) for open channel flow.

channel material	Manning's n
Concrete	
trowel finish	0.013
float finish	0.015
Concrete bottom with rubble or riprap sides	0.030
Vegetation	
depth of flow up to 0.7 ft (215 mm)	
lawns cut 4 to 6 inches	0.070
good stand cut to 12 inches	0.140
good stand cut to 24 inches	0.250
fair stand cut to 12 inches	0.120
fair stand cut to 24 inches	0.200
depth of flow 0.7 to 1.5 ft (215 to 450 mm)	
lawns cut 4 to 6 inches	0.050
good stand cut to 12 inches	0.100
good stand cut to 24 inches	0.150
fair stand cut to 12 inches	0.080
fair stand cut to 24 inches	0.140
Bare soil	
recently completed	0.018
clean after weathering	0.022
Rock cut	
smooth and uniform	0.035
jagged and irregular	0.040

After calculating velocity, use Equation 4A-5_5 to determine ($T_{c\ swale}$).

To estimate $T_{c\ swale}$, the design flow, Q, is desired to estimate flow depth in order to estimate wetted perimeter (P_{wetted}). However, T_c is required to estimate Q; therefore, this is an iterative process that is simplified by hydraulic computer models and spreadsheets. The general design process should be understood before using a model and checking results.

Calculating Peak Flow (Q) for a Drainage Area

The following example demonstrates the process for determining peak flow for a drainage area.

Example Problem 4a-05_4, Determining Peak Flow Values

Design Application

Distinct parts of a drainage area may produce higher peak flows than if a composite 'C' value is used for the total drainage area. Each of these parts should be examined individually, as well as in combination, to determine which produces the largest peak flow. When determining Q for the composite area, use the flowpath associated with the longest T_c.

Runoff analysis must consider flow from outside the study area that may enter the site either as surface runoff or as contained flow in tiles and pipes.

In addition to the determination and analysis of existing and proposed design flows for each design event, consideration must be given to interim construction conditions, staged construction, and reconstruction

Interim Construction Conditions

During construction, vegetative cover may be diminished resulting in increased runoff coefficients and peak flows. Proposed design flow determinations may not be adequate to evaluate interim construction conditions (including erosion and sediment control needs).

Inlets are generally protected from sediment by erosion control devices, such as filter socks, which can trap runoff. Evaluate potential ponding and impacts caused by such erosion control devices.

Sediment basins may be desired to both store excess runoff and capture excess sediment.

Staged Construction

Designers occasionally need to select temporary drainage structures to accommodate staged construction. The level of design required must be commensurate with the risks (including traffic, speed, location, etc.) and should be discussed and selected by the design team.

Reconstruction

Generally reconstruction results in replacing or upgrading a storm sewer system. Occasionally the contributing runoff area has been modified either by overland contribution or closed system contribution (from other storm drain systems that have been tapped into the project area system). Quite often design parameters (e.g. design flow) and design coefficients (impervious area) have changed since the original system design. However, don't reduce the number or size of existing inlets or pipes without significant design evaluation and concurrence from the local and maintenance authorities.

Chronology of Changes to Design Manual Section:

004A-005 Using the Rational Method to Determine Peak Flow

7/2/2015 Revised

Revised Rainfall Intensity tables to NOAA-14 data. Deleted metric information. Revised Example problems 4A-5_2 and 4A-5_4.

11/30/2010 Revised

Rewritten material from old 4A-4. Material in old 4A-5 moved to 4A-6.