

APPENDIX F – RATIONAL METHOD

1.0 Introduction

One of the most commonly used procedures for calculating peak flows from small drainages less than 200 acres is the Rational Method. This method is most accurate for runoff estimates from small drainages with large amounts of impervious area. Examples are housing developments, industrial areas, parking lots, etc. The Rational Method is included in the HYDROLOGIC module of the FHWA's Watershed Modeling System computer software package and a Rational Method calculator is available within the FHWA Hydraulics Toolbox program. Input data such as runoff coefficients, rainfall information, etc., should be based on the procedures and information in the ODOT Hydraulics Manual when using this program.

2.0 Rational Equation

The Rational Method (or Rational Formula) is:

$$Q = C_f C i A \quad (\text{Equation 1})$$

Where:

- Q = Peak flow in cubic feet per second (cfs)
- C_f = Runoff coefficient adjustment factor to account for reduction of infiltration and other losses during high intensity storms
- C = Runoff coefficient to reflect the ratio of rainfall to surface runoff
- i = Rainfall intensity in inches per hour (in/hr)
- A = Drainage area in acres (ac)

Limitations and assumptions in the Rational Method are as follows:

- The drainage area should not be larger than 200 acres.
- The peak flow is assumed to occur when the entire watershed is contributing runoff.
- The rainfall intensity is assumed to be uniform over a time duration equal to or greater than the time of concentration, T_c .
- The peak flow recurrence interval is assumed to be equal to the rainfall intensity recurrence interval. In other words, the 10-year rainfall intensity is assumed to produce the 10-year flood.

Detailed descriptions of the Rational Method input variables follow:

- **Runoff Coefficient "C"** - This variable represents the ratio of runoff to rainfall. It is the most difficult input variable to estimate. It represents the interaction of many complex factors, including the storage of water in surface depressions, infiltration, antecedent moisture, ground cover, ground slopes, and soil types. In reality, the coefficient may vary with respect to prior wetting and seasonal conditions. The use of average values has been adopted to simplify the determination of this coefficient. Table 1 lists runoff coefficients for various combinations of ground cover and slope. Where a drainage area is composed of subareas with different runoff coefficients, a composite coefficient for the total drainage area is computed by dividing the summation of the products of the subareas and their coefficients by the total area:

$$\text{Composite } C = \frac{\sum (C_{\text{Individual Areas}})(A_{\text{Individual Areas}})}{A_{\text{Total Area}}} \quad (\text{Equation 2})$$

The impervious surface area is often a factor in stormwater storage and water quality treatment designs. Impervious surfaces have runoff coefficients greater than 0.80 based on Table 1. These are hard surfaces which either prevent or significantly retard the entry of water into the soil mantle. Common impervious surfaces include, but are not limited to, roof tops, walkways, patios, driveways, parking lots or other storage areas, concrete or asphalt paving, gravel roads, packed earthen materials, oiled, macadam, or other similar surfaces.

- **Runoff Coefficient Adjustment Factor "C_f"** - The coefficients in Table 1 are applicable for 10-years or less recurrence interval storms. Less frequent, higher intensity storms require adjusted runoff coefficients because infiltration and other losses have a proportionally smaller effect on runoff. Runoff coefficient adjustment factors (C_f) for storms of different recurrence intervals are listed in Table 2.
- **Rainfall Intensity "i"** - This variable indicates rainfall severity. Rainfall intensity is related to rainfall duration and design storm recurrence interval. Rainfall intensity at a duration equal to the time of concentration (T_c) is used to calculate the peak flow in the Rational Method. The rainfall intensity can be selected from the appropriate intensity-duration-recurrence interval (I-D-R) curve in [Appendix A](#).
- **Area "A"** - The area is defined as the drainage surface area in acres, measured in a horizontal plane. The area is usually measured from plans or maps using a planimeter. The area includes all land enclosed by the surrounding drainage divides. In highway drainage design, this area will frequently include upland properties beyond the highway right-of-way.

Table 1 Runoff Coefficients for the Rational Method

	FLAT	ROLLING	HILLY
Pavement & Roofs	0.90	0.90	0.90
Earth Shoulders	0.50	0.50	0.50
Drives & Walks	0.75	0.80	0.85
Gravel Pavement	0.85	0.85	0.85
City Business Areas	0.80	0.85	0.85
Apartment Dwelling Areas	0.50	0.60	0.70
Light Residential: 1 to 3 units/acre	0.35	0.40	0.45
Normal Residential: 3 to 6 units/acre	0.50	0.55	0.60
Dense Residential: 6 to 15 units/acre	0.70	0.75	0.80
Lawns	0.17	0.22	0.35
Grass Shoulders	0.25	0.25	0.25
Side Slopes, Earth	0.60	0.60	0.60
Side Slopes, Turf	0.30	0.30	0.30
Median Areas, Turf	0.25	0.30	0.30
Cultivated Land, Clay & Loam	0.50	0.55	0.60
Cultivated Land, Sand & Gravel	0.25	0.30	0.35
Industrial Areas, Light	0.50	0.70	0.80
Industrial Areas, Heavy	0.60	0.80	0.90
Parks & Cemeteries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland & Forests	0.10	0.15	0.20
Meadows & Pasture Land	0.25	0.30	0.35
Unimproved Areas	0.10	0.20	0.30

Note:

- **Impervious surfaces in bold**
- *Rolling = ground slope between 2 percent to 10 percent*
- *Hilly = ground slope greater than 10 percent*

Table 2 Runoff Coefficient Adjustment Factors

<u>RECURRENCE INTERVAL</u>	<u>RUNOFF COEFFICIENT ADJUSTMENT FACTOR</u>
10 years or less	1.0
25 years	1.1
50 years	1.2
100 years	1.25

- Time of Concentration "T_c"** - The time of concentration (T_c), is defined as the time it takes for runoff to travel from the hydraulically most distant point in the watershed to the point of reference downstream. Most drainage paths consist of overland flow segments as well as channel flow segments. The overland flow component can be further divided into a sheet flow segment and a shallow concentrated flow segment. Urban drainage basins often will have one or more pipe flow segments. The travel time is computed for each flow segment and the time of concentration is equal to the sum of the individual travel times, as follows:

$$T_c = T_{osf} + T_{scf} + T_{ocf} + T_{pf} \quad (\text{Equation 3})$$

Where:

- T_c = Time of concentration in minutes (min.)
- T_{osf} = Travel time for the overland sheet flow segment in minutes (min.)
- T_{scf} = Travel time for the shallow concentrated flow segment in minutes (min.)
- T_{ocf} = Travel time for the open-channel flow segment(s) in minutes (min.)
- T_{pf} = Travel time for the pipe flow segment(s) in minutes (min.)

The drainage path used to determine the time of concentration need not include all of the listed segments. As an example, a roadway pavement bounded by curbs and drained by an inlet connected to a storm drain will have segments of overland sheet flow (pavement), open-channel flow (gutter), and pipe flow (storm drain). There is no shallow concentrated flow segment.

The travel times for the flow segments are determined as follows.

- Overland Sheet Flow** - Overland sheet flow is shallow flow over a plane surface. It occurs in the furthest upstream segment of the drainage path, which is located immediately downstream from the drainage divide. The length of the overland sheet flow segment is the shorter of: the distance between the drainage divide and the upper end of a defined channel,

or a distance of 300 feet. The overland sheet flow velocity is usually slower than the velocities further downstream.

The kinematic wave equation can be used to estimate the time of concentration associated with overland sheet flow. The equation is shown below, and it is only applicable for travel

$$T_{\text{osf}} = \frac{0.93(L^{0.6}n^{0.6})}{(i^{0.4}S^{0.3})} \quad (\text{Equation 4})$$

distances equal to or less than 300 feet.

Where:

T_{osf} = Travel time for the overland sheet flow segment in minutes (min.)

L = Length of the overland sheet flow segment in feet (ft)

n = Manning's roughness coefficient (See Table 3)

i = Rainfall intensity in inches per hour (in/hr) See [Appendix A](#).

S = The average slope of the overland area in feet per feet (ft/ft)

Note: Calculating the time of concentration for overland sheet flow is an iterative or trial and error solution because both the flow time and the rainfall intensity are unknown. The procedure is illustrated in the Example.

Table 3 Manning's Roughness Coefficients for Overland Sheet Flow

(Maximum Flow Depth = 1 inch)

Pavement & Roofs	0.014
City Business Areas	0.014
Graveled Surfaces	0.020
Apartment Dwelling Areas	0.050
Industrial Areas	0.050
Urban Residential Areas (more than 6 units acre)	0.080
Meadows, Pastures & Range Land	0.150
Rural Residential Areas (more than 6 units acre)	0.240
Playgrounds, Light Turf	0.240
Parks & Cemeteries, Heavy Turf	0.400
Woodland & Forests	0.400

- **Shallow Concentrated Flow** - Overland sheet flow often becomes either shallow concentrated flow or open-channel flow as it progresses down the drainage. It becomes

shallow concentrated flow if it enters a shallow or poorly defined channel such as a gully or rill. The average shallow concentrated flow velocity can be approximated using Figure 1, in which the velocity is a function of the watercourse slope and the surface type. The travel

$$T_{scf} = \frac{L}{60V} \quad (\text{Equation 5})$$

time for the shallow concentrated flow segment is calculated by the following formula:

Where:

T_{scf} = Travel time for the shallow concentrated flow segment in minutes (min.)

L = Length of the shallow concentrated flow segment in feet (ft)

V = Average flow velocity in feet per second (ft/s), as shown in Figure 1.

Note: This figure is from the 1972 "Soil Conservation Service Handbook".

- **Open-Channel and Pipe Flow** - Overland sheet flow, or shallow concentrated flow, becomes open-channel flow when it enters a defined channel with known cross-sectional geometry, a channel visible on aerial photographs, or a channel indicated by a blue line on a USGS 7.5 - minute quadrangle map. Sheet or shallow concentrated flow becomes pipe flow when it enters a closed conduit such as a culvert or storm drain. The velocities in the segments of the drainage path with open-channel or pipe flow are determined by Manning's equation. Once the velocity is known, the travel time for the segment is calculated by dividing the segment length by the velocity. The procedure is similar to the method used with Equation 5 for shallow concentrated flow. Flows in open-channels, conduits and gutters are discussed in **Chapter 8**.

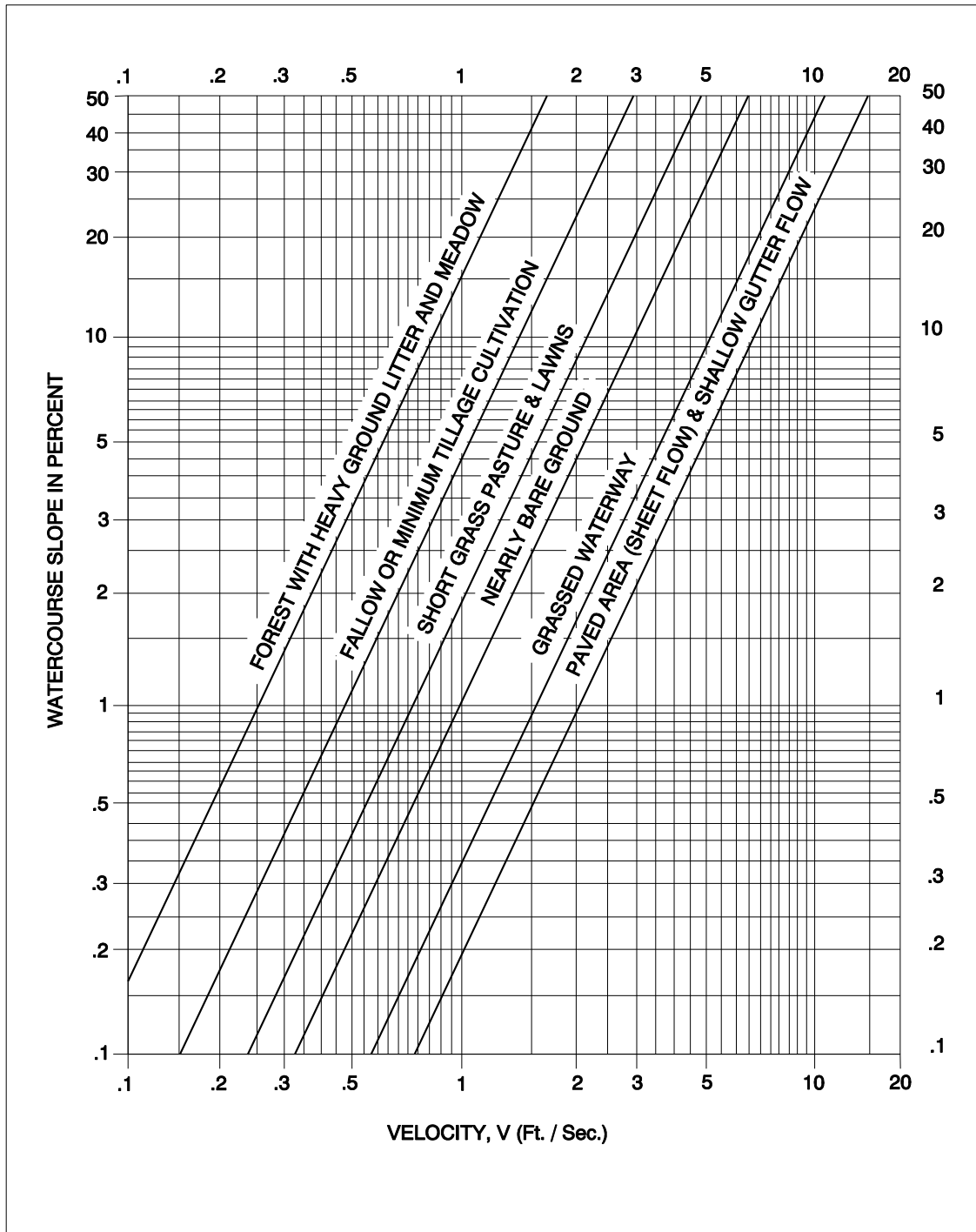


Figure 1 Shallow Concentrated Flow Velocities

3.0 Discharges at Junctions

The locations where tributary subbasin and basin drainage paths connect to each other are called flow junctions or junctions. An important part of a hydraulic analysis is to determine the peak discharges that will pass through these junctions. In many cases, it can be assumed that the peak discharge occurs when the entire upstream drainage area is contributing flow. This occurs when the storm duration is equal to the time of concentration of the tributary with the longest time of concentration, based on the assumptions used in the Rational Method.

The preceding assumption is not valid in some instances. Sometimes the peak discharge at a junction occurs when the storm duration corresponds to the time of concentration of the tributary with a shorter time of concentration. When this occurs, the entire drainage area of the tributary with the shorter time of concentration will be contributing flow, and only a portion of the drainage area with the longer time of concentration will be contributing runoff. The runoff from the more remote portions of the drainage basin with the longer time of concentration will not yet have arrived at the junction.

The designer should be aware that the peak flow at a junction can occur when the storm duration corresponds to the time of concentration of a tributary, and this possibility should be checked at critical junctions. **This situation is most likely at junctions where the flow from a large and impervious subbasin with a shorter time of concentration joins the discharge from an upstream subbasin that is mostly pervious with a longer time of concentration.** The following procedure can be used to determine discharges into junctions.

Step 1 - Calculate the times of concentration of the various tributaries upstream from the junction. For tributaries A, B ... n, these are T_{cA} , T_{cB} ... T_{cn} . For the sake of organization, order the tributaries successively based on time of concentration. The tributary with the longest time of concentration is Tributary A, the tributary with the next longest time of concentration is Tributary B, etc.

Step 2 - Calculate the discharges from Tributaries A, B n using the rainfall intensity corresponding to T_{cA} . This is i_A . The full drainage area of each tributary is contributing runoff. The formulae to calculate the discharges from each tributary, based on Equation 1, are:

$$Q_A = (C_f) (C_A) (i_A) (A_A)$$

$$Q_B = (C_f) (C_B) (i_A) (A_B)$$

$$Q_n = (C_f) (C_n) (i_A) (A_n)$$

The total flow into the junction is $Q_{Total} @ T_{cA} = Q_A + Q_B + \dots Q_n$

- Step 3** - Recalculate the discharges from Tributaries A, B ... n using the rainfall intensity corresponding to T_{cB} . This is i_B . Only a portion of the drainage area of the tributary with the longer time of concentration will contribute runoff. In this case, it would be Tributary A. Use the ratio of the times of concentration to determine the portion that contributes runoff, as follows:

$$Q_A = (C_f) (C_A) (i_B) \left(\frac{T_{cB}}{T_{cA}} \right) (A_A)$$

The full drainage area of each tributary that has an equal or shorter time of concentration will contribute runoff. These are tributaries B ... n. The formulae to calculate the discharges are:

$$Q_B = (C_f) (C_B) (i_B) (A_B)$$

$$Q_n = (C_f) (C_n) (i_B) (A_n)$$

The total flow into the junction is $Q_{Total} @ T_{cB} = Q_A + Q_B + \dots Q_n$

- Step 4** - Recalculate the discharges from Tributaries A, B ... n using the rainfall intensity corresponding to T_{cn} . This is i_n . Only portions of the drainage areas of the tributaries with the longer times of concentration will contribute runoff. In this case, this would be Tributaries A and B. Use the ratios of the times of concentration to determine the portions that contribute runoff, as follows:

$$Q_A = (C_f) (C_A) (i_n) \left(\frac{T_{cn}}{T_{cA}} \right) (A_A)$$

$$Q_B = (C_f) (C_B) (i_n) \left(\frac{T_{cn}}{T_{cB}} \right) (A_B)$$

and

$$Q_n = (C_f) (C_n) (i_n) (A_n)$$

The total flow into the junction is $Q_{Total} @ T_{cn} = Q_A + Q_B + Q_n$

- Step 5** - Compare the total discharges into the junction based on the different times of concentration. In this case this would be the results of Steps 2, 3, and 4. The highest total discharge governs, and it is to be used in the design or analysis.

4.0 Example Problem 1 - Rational Method

Several urban residential lots are the first drainage basin of a storm drain system. The 10-year time of concentration (T_c), and discharge (Q) are needed. The lots are small and it is assumed that runoff will be overland sheet flow. The project location data contains the following:

- Basin area (A) = 1.24 acres
- Length of overland flow (L) = 164 feet
- Basin slope (S) = 0.02 feet/foot
- Development density = 10 housing units per acre
- Basin is in Imnaha

From Table 3: Manning's "n" for overland flow = 0.08 (value for an urban residential area)

From the [I-D-R Curve Zone Map in Appendix A](#): Imnaha is in Zone 10

A time of concentration (T_c) is assumed, and the corresponding rainfall intensity (i) is determined from Zone 10 I-D-R curve for a 10-year intensity. Values from this curve are used in the kinematic wave equation (Equation 4) to calculate the T_c , and the calculated T_c is compared to the assumed T_c . If the calculated and assumed T_c values are the same, then the solution for T_c has been found. If the calculated and assumed T_c values are different, a new T_c and corresponding i are used in Equation 4. This procedure is repeated until the calculated T_c is in agreement with the assumed T_c , as follows:

Iteration 1: Assuming $T_c = 5$ minutes, $i = 2.2$ inches per hour. Calculated $T_c = 10$ minutes.

$$T_c = 0.93 \frac{(164^{0.6})(0.08^{0.6})}{(2.2^{0.4})(0.02^{0.3})} = 10 \text{ minutes}$$

Assumed and calculated T_c are not the same. Perform a second iteration.

Iteration 2: Assuming $T_c = 12$ minutes, $i = 1.6$ inches per hour. Calculated $T_c = 12$ minutes.

$$T_c = 0.93 \frac{(164^{0.6})(0.08^{0.6})}{(1.6^{0.4})(0.02^{0.3})} = 12 \text{ minutes}$$

Since the assumed and calculated T_c are in agreement, $T_c = 12$ minutes and $i = 1.6$ inches per hour. Use of the I-D-R curve is shown in Figure 2.

From Table 2: $C_f = 1.0$ for a 10-year recurrence interval.

From Table 1: $C = 0.75$ (rolling terrain, dense residential with 6 to 15 units per acre)

The discharge is calculated using the Rational Method (Equation 1) as follows:

$$Q_{10} = (1.0) (0.75) (1.6) (1.24) = 1.5 \text{ cubic feet per second}$$

5.0 Example Problem 2 - Rational Method

Drainage from the basin shown in Figure 3 flows to a highway culvert crossing. Peak flow is needed for a 50-year design storm using the Rational Method, $Q = C_f C_i A$. The project is in Bend. A runoff coefficient adjustment factor (C_f) is needed because peak flow is to be determined for a 50-year storm. From Table 2, the adjustment factor is: $C_f = 1.2$

A composite runoff coefficient (C) is needed because the drainage basin contains subareas with different C values. Subarea C values are from Table 1, and the composite C value is calculated as follows:

<u>Description</u>	<u>"C" Value</u>	<u>Area (acres)</u>	<u>Impervious Area $C_i A_i$ (acres)</u>
Rolling Forest	0.15	3.2	0.5
Flat Light Residential	0.35	3.0	1.1
Flat Pasture	0.25	4.7	1.2
	Total	10.9	2.8

The composite runoff coefficient is calculated using Equation 2 as follows:

$$C = \frac{(0.5 + 1.1 + 1.2)}{10.9} = \frac{2.8}{10.9} = 0.26$$

The area (A) is also calculated during this step: $A = 10.9$ acres

The rainfall intensity (i) is needed. The Bend area is in Zone 10 according to the [I-D-R Curve Index in Appendix A](#). The 50-year curve will be used. The time of concentration (T_c) must first be estimated to obtain the rainfall intensity. For this example, the drainage path used to determine the time of concentration is composed of two segments. The first segment is 300 feet long and it is assumed to be overland sheet flow. The remaining 900-foot long segment is assumed to be shallow concentrated flow.

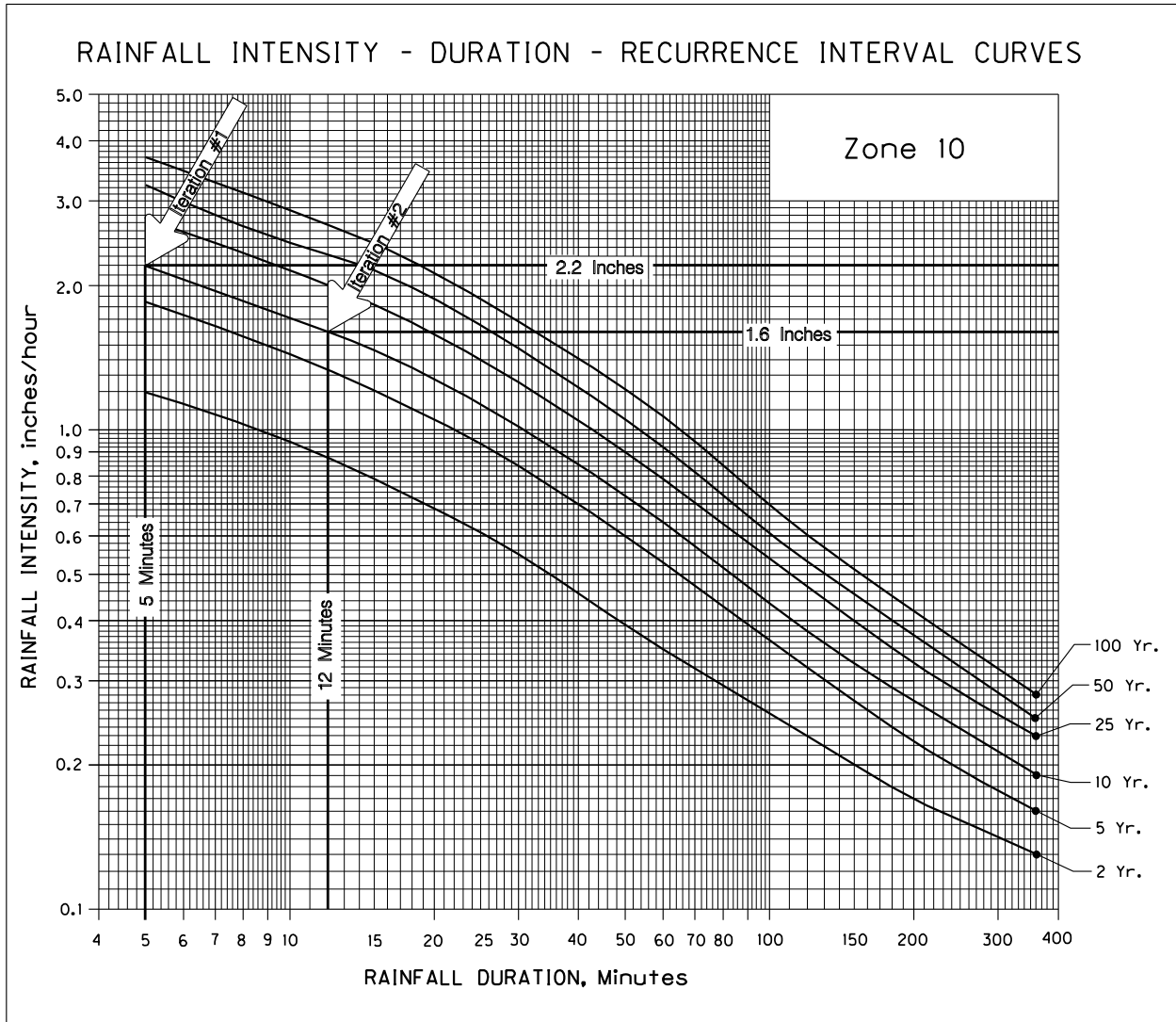


Figure 2 Use of I-D-R Curve

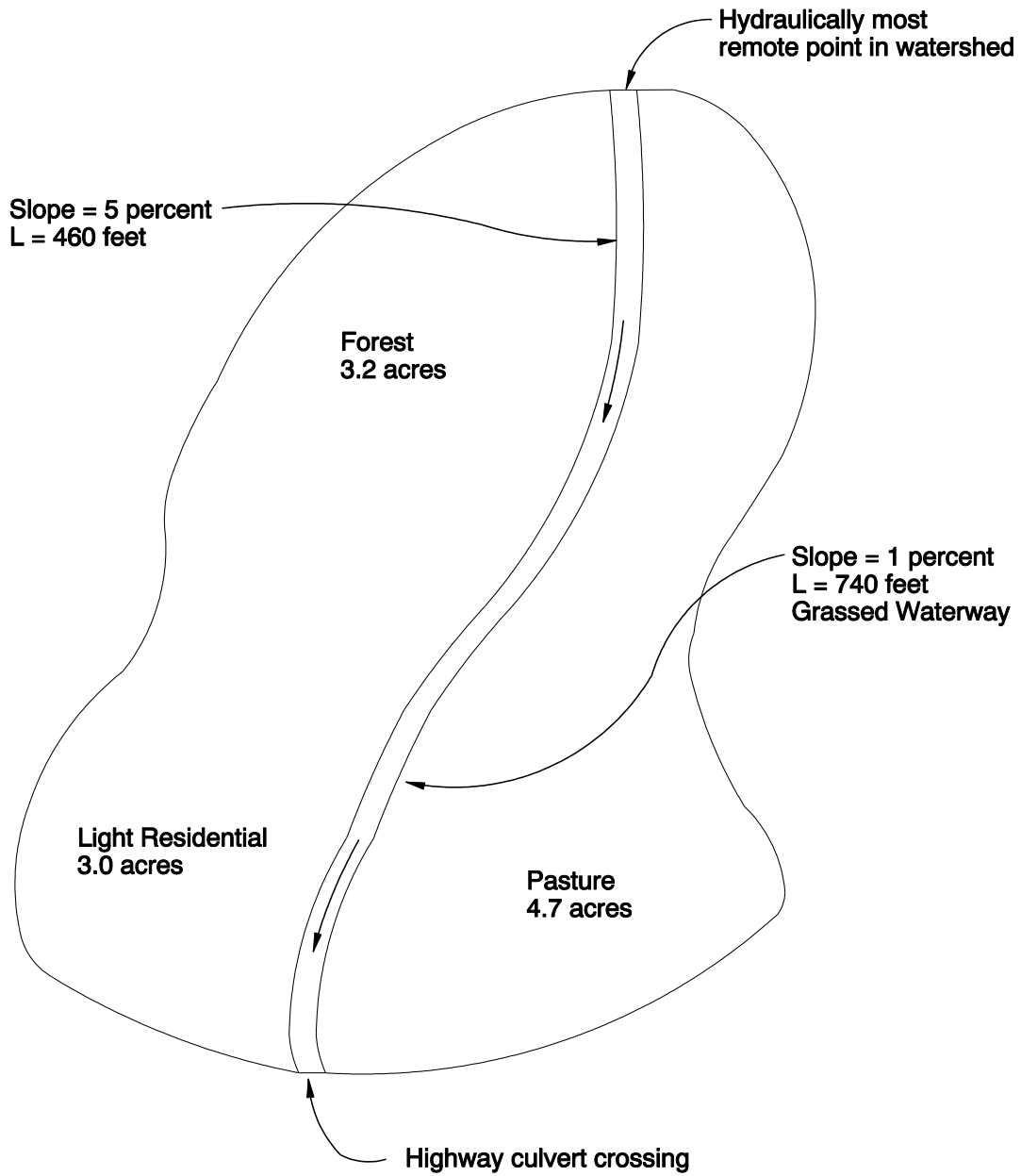


Figure 3 Drainage Basin Near Bend, Oregon

Overland Sheet Flow Segment - The travel time for the overland sheet flow segment is calculated as follows.

From Table 3: $n = 0.40$ (woodland and forest)

$$\text{From Equation 4: } T_{\text{osf}} = 0.93 \frac{(300^{0.6} 0.4^{0.6})}{(i^{0.4} 0.05^{0.3})} = \frac{40.4}{i^{0.4}}$$

From the 50-year Zone 10 I-D-R curve, and using a trial and error solution: $T_{\text{osf}} = 36$ minutes

Shallow Concentrated Flow Segment - The travel time for the shallow concentrated flow segment is calculated as follows.

From the location data, 160 feet of the drainage path is over forested land with a 5 percent slope: $L = 160$ feet, and $S = 5$ percent

From Figure 1: $V = 0.575$ feet per second

From Equation 5, the travel time for shallow concentrated flow over forested land is:

$$T_{\text{scf}} (\text{forested land}) = \frac{160}{(60)(0.575)} = 5 \text{ minutes}$$

From the location data, the last 740 feet of the drainage path is a grassed waterway at a 1 percent slope: $L = 740$ feet, and $S = 1$ percent

From Figure 1: $V = 1.5$ feet per second

The travel time for shallow concentrated flow down the grassed waterway is:

$$T_{\text{scf}} (\text{grassed waterway}) = \frac{740}{(60)(1.5)} = 8 \text{ minutes}$$

From Equation 3, the time of concentration is: $T_c = 36 + 5 + 8 = 49$ minutes

From the 50-year Zone 10 I-D-R curve using a rainfall duration that corresponds to the 49-minute time of concentration: $i = 1.07$ inches per hour

From Equation 1, the peak flow is calculated as follows:

$$Q_{50} = (1.2) (0.26) (1.07) (10.9) = 3.6 \text{ cubic feet per second}$$