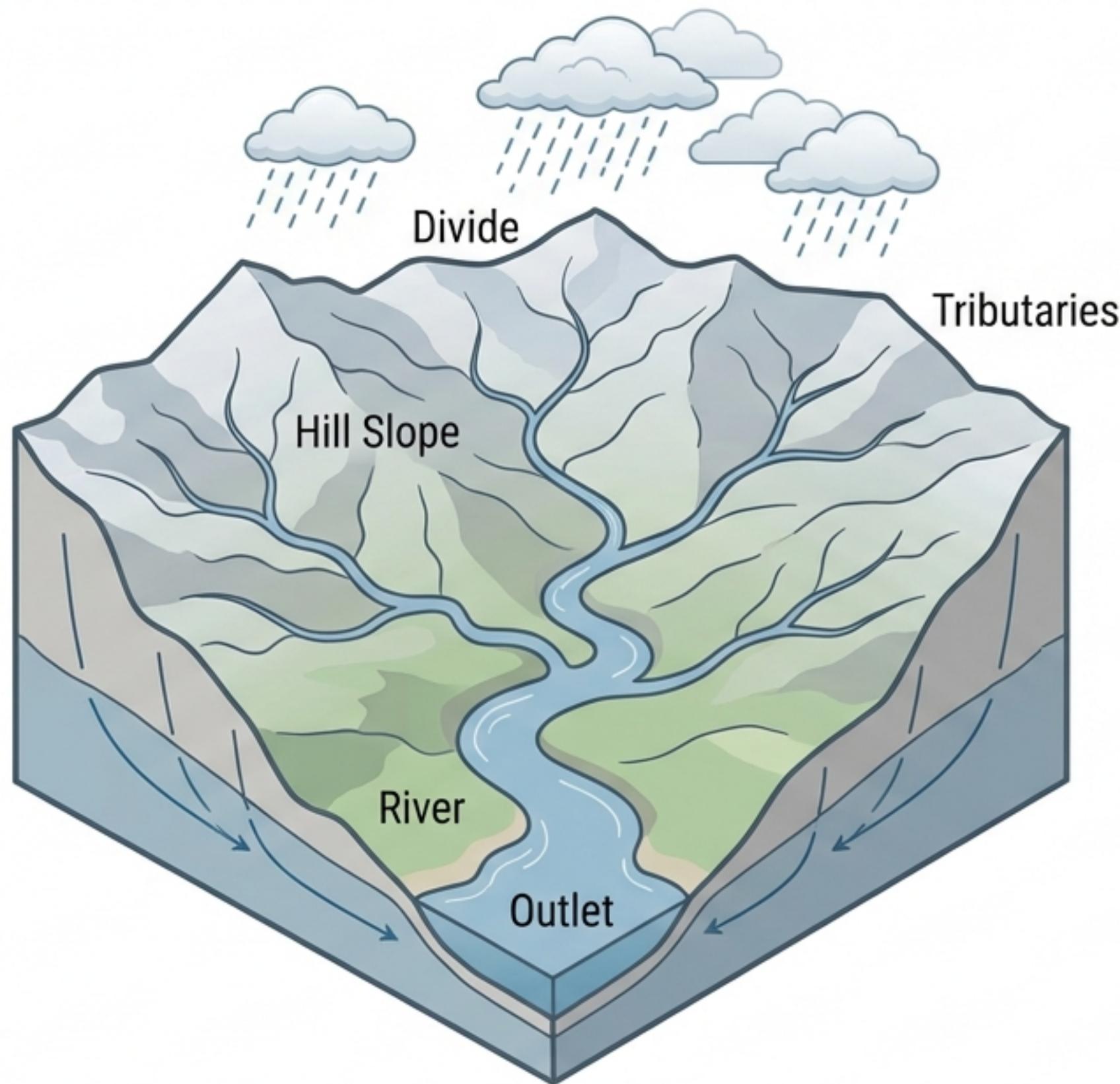
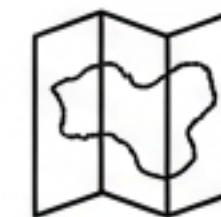


# **Engineering the Storm: Principles of Hydrology & Urban Water Management**

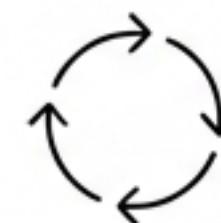
**From Watersheds to Hydrographs: Quantifying  
and Managing Runoff in the Built Environment.**



# The Fundamental Unit: The Watershed



A watershed is an area of land where all of the water that falls under it and drains off of it goes to a common outlet.

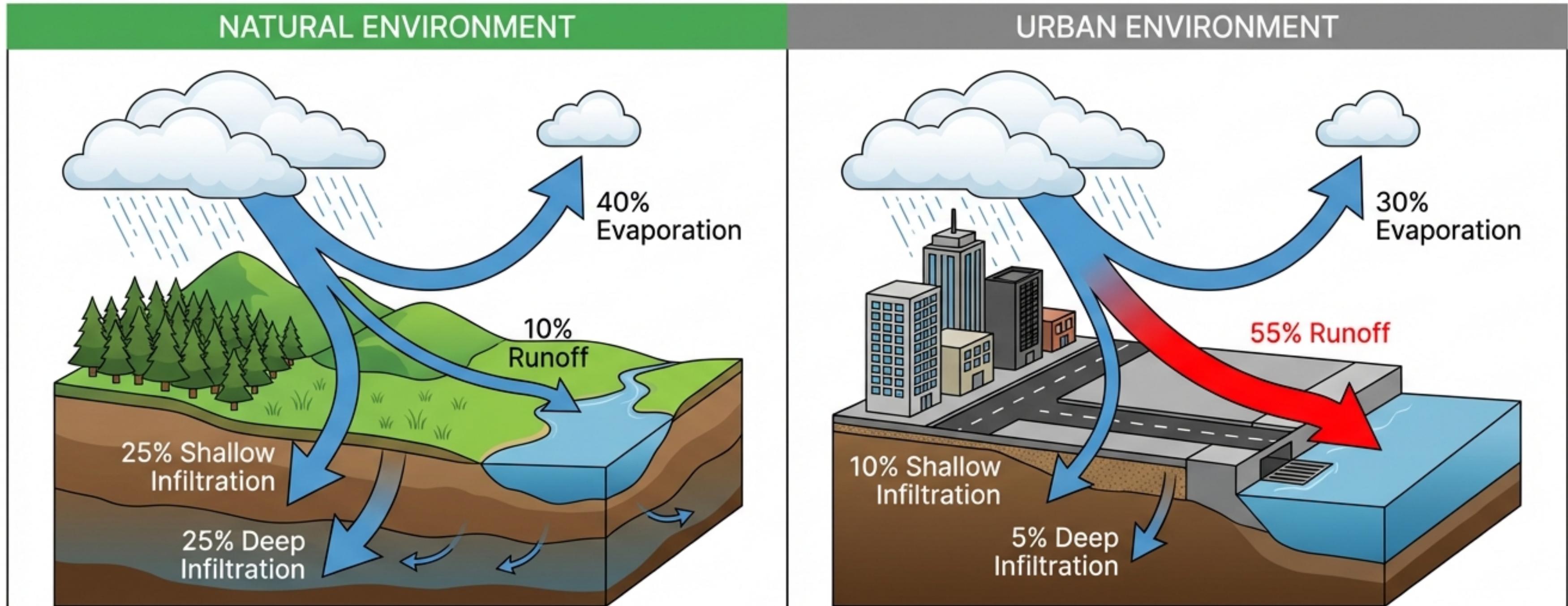


Water is in constant motion—evaporation, transpiration, precipitation, and runoff.



In a natural state, the cycle is balanced. In an engineered environment, we must calculate how much of that precipitation becomes 'Direct Runoff' versus how much is lost to infiltration and evaporation.

# The Conflict: Urbanization vs. Infiltration

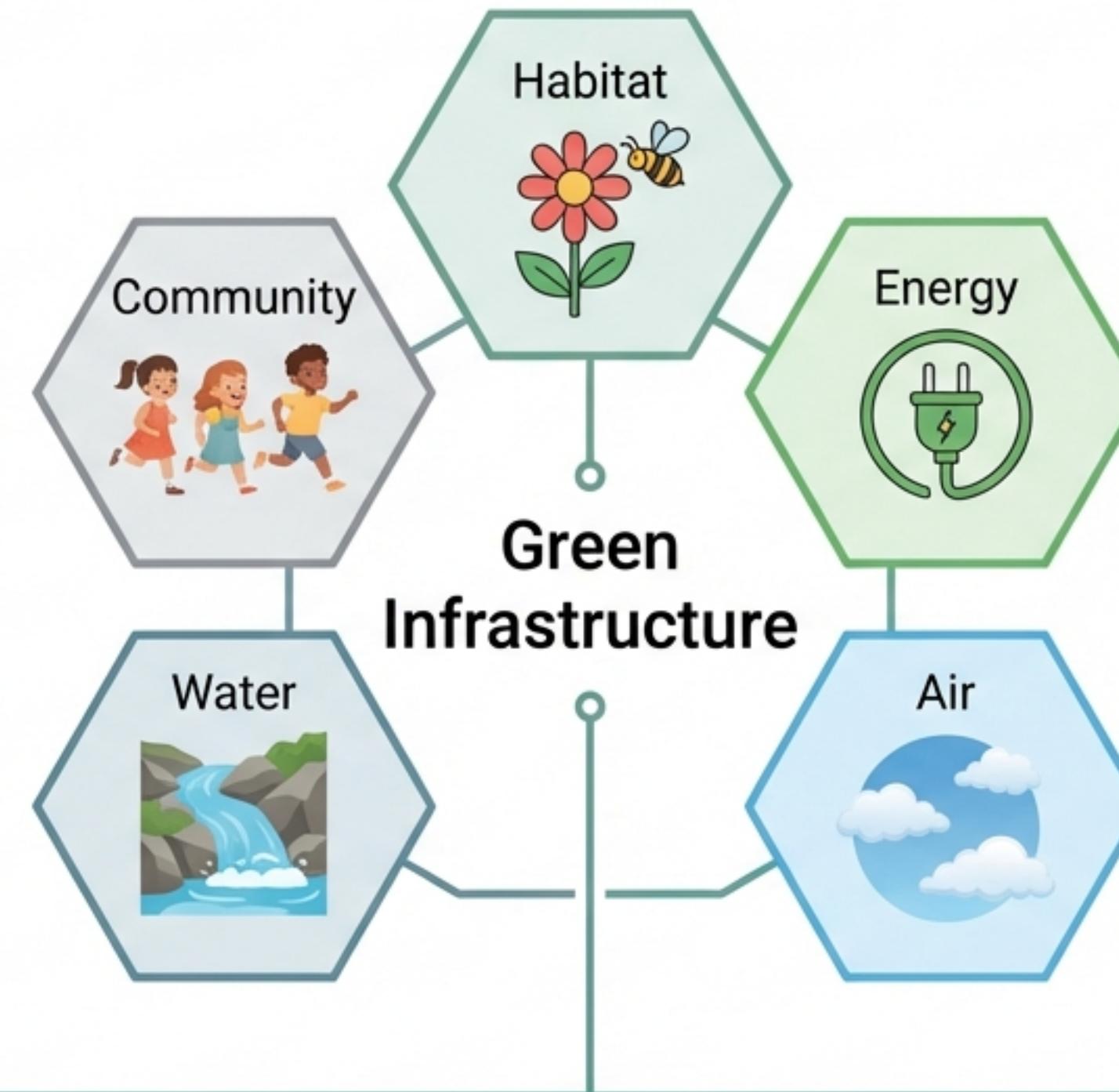


"As we replace soil with concrete, we lose the earth's natural sponge. In New York City, for example, the land is more than 66% impervious. This shift requires precise engineering to handle the excess volume."

# Gray vs. Green: A Philosophy of Management

**Gray Infrastructure**

Single-purpose. Uses pipes to dispose of rainwater quickly.



**Green Infrastructure**

Multi-functional. Uses vegetation and soil to manage rainwater where it falls.

**Core Benefit:** By weaving natural processes into the built environment, we achieve stormwater management alongside flood mitigation and air quality improvement.

# Input Data: Quantifying Rainfall

Engineers characterize storms by three metrics: Depth, Duration, and Frequency.

Duration	1	2	5	10
5-min	0.5 (0.01-0.92)	4.7 (0.21-1.03)	3.1 (0.57-1.06)	5.4 (0.91-1.1)
10-min	0.00 (0.07-1.02)	0.05 (0.51-1.35)	1.15 (0.31-1.89)	1.20 (0.53-1.8)
15-min	0.81 (0.07-1.26)	10.3 (0.61-1.81)	15.5 (0.42-1.99)	16.7 (0.36-2.1)
15-min	0.20 (0.07-1.34)	0.30 (0.61-1.96)	1.53 (0.85-2.02)	2.00 (0.01-2.7)
30-min	0.08 (0.07-1.55)	0.60 (0.39-2.03)	0.75 (0.03-2.29)	2.33 (0.16-2.7)
60-min	0.99 (0.03-1.07)	0.70 (0.73-2.41)	9.07 (0.73-2.56)	2.56 (0.99-3.0)
2-hr	0.99 (0.01-1.04)	0.99 (0.91-2.07)	1.25 (0.06-2.60)	1.91 (0.51-2.0)
3-hr	0.99 (0.07-1.07)	1.09 (0.18-2.82)	1.56 (0.12-2.82)	1.56 (0.31-3.1)
6-hr	1.00 (0.08-1.08)	1.10 (0.17-2.03)	1.91 (0.34-2.84)	2.01 (0.31-3.5)
12-hr	0.94 (0.10-1.98)	1.21 (0.23-1.89)	2.45 (0.26-2.39)	2.51 (0.23-3.0)
24-hr	1.00 (0.01-1.84)	1.57 (0.21-1.23)	2.65 (0.39-2.56)	2.73 (6.31-3.6)
2-day	1.33 (0.29-1.13)	1.78 (0.25-2.35)	2.31 (0.25-3.96)	2.98 (3.61-4.0)
3-day	1.37 (0.13-1.57)	1.95 (0.28-2.39)	2.38 (0.34-3.49)	3.08 (0.55-4.0)
4-day	1.80 (0.17-2.02)	1.93 (0.58-3.06)	2.40 (0.51-4.04)	3.55 (0.31-4.5)
7-day	1.83 (0.06-2.30)	2.10 (0.34-3.36)	2.35 (0.05-4.01)	3.56 (0.76-4.5)
10-day	2.17 (0.16-2.69)	2.24 (0.21-3.79)	2.67 (0.85-4.54)	3.98 (0.67-5.0)
20-day	2.29 (0.22-2.57)	2.46 (0.53-3.31)	2.80 (0.81-5.01)	3.77 (0.73-5.6)
30-day	2.90 (0.29-3.10)	2.43 (8.57-3.52)	3.33 (0.91-5.36)	4.18 (0.76-5.7)
45-day	2.30 (0.25-2.38)	2.45 (0.32-3.88)	3.70 (0.51-4.91)	4.73 (0.93-5.8)
60-day	3.18 (0.13-1.98)	3.35 (0.37-3.89)	4.21 (0.72-4.54)	5.30 (0.95-6.2)

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches) <sup>1</sup>										
Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	
5-min	0.334 (0.303-0.368)	0.397 (0.360-0.438)	0.471 (0.426-0.519)	0.524 (0.474-0.577)	0.589 (0.530-0.648)	0.634 (0.568-0.697)	0.680 (0.606-0.748)	0.720 (0.638-0.793)	0.771 (0.677-0.851)	0.808 (0.705-0.895)
10-min	0.533 (0.484-0.588)	0.635 (0.577-0.700)	0.754 (0.682-0.831)	0.838 (0.758-0.923)	0.938 (0.844-1.03)	1.01 (0.904-1.11)	1.08 (0.962-1.19)	1.14 (1.01-1.26)	1.22 (1.07-1.35)	1.27 (1.11-1.41)
15-min	0.666 (0.605-0.735)	0.799 (0.725-0.881)	0.954 (0.863-1.05)	1.06 (0.958-1.17)	1.19 (1.07-1.31)	1.28 (1.15-1.41)	1.37 (1.22-1.50)	1.44 (1.28-1.59)	1.53 (1.35-1.69)	1.60 (1.39-1.77)
30-min	0.913 (0.829-1.01)	1.10 (1.00-1.22)	1.36 (1.23-1.49)	1.54 (1.39-1.69)	1.76 (1.59-1.94)	1.93 (1.73-2.12)	2.09 (1.86-2.30)	2.24 (1.99-2.47)	2.44 (2.14-2.70)	2.59 (2.26-2.86)
60-min	1.14 (1.03-1.26)	1.38 (1.26-1.53)	1.74 (1.57-1.92)	2.00 (1.81-2.20)	2.35 (2.11-2.58)	2.61 (2.34-2.87)	2.88 (2.57-3.17)	3.15 (2.79-3.47)	3.50 (3.08-3.87)	3.78 (3.30-4.18)
2-hr	1.39 (1.25-1.55)	1.70 (1.53-1.88)	2.15 (1.94-2.39)	2.51 (2.25-2.78)	3.00 (2.67-3.32)	3.40 (3.02-3.76)	3.81 (3.36-4.22)	4.24 (3.72-4.70)	4.84 (4.19-5.38)	5.32 (4.57-5.92)
3-hr	1.55 (1.40-1.73)	1.89 (1.70-2.10)	2.40 (2.16-2.67)	2.80 (2.51-3.11)	3.35 (2.99-3.71)	3.80 (3.37-4.21)	4.26 (3.76-4.73)	4.75 (4.16-5.27)	5.43 (4.69-6.04)	5.97 (5.11-6.66)
6-hr	1.99 (1.79-2.22)	2.41 (2.17-2.69)	3.06 (2.75-3.40)	3.59 (3.21-3.97)	4.34 (3.85-4.80)	4.97 (4.38-5.48)	5.65 (4.93-6.23)	6.38 (5.52-7.02)	7.43 (6.33-8.19)	8.30 (6.99-9.16)
12-hr	2.42 (2.18-2.72)	2.94 (2.64-3.30)	3.75 (3.36-4.20)	4.44 (3.96-4.95)	5.45 (4.82-6.06)	6.33 (5.55-7.02)	7.28 (6.31-8.06)	8.34 (7.14-9.24)	9.90 (8.33-11.0)	11.2 (9.31-12.5)
24-hr	2.76 (2.55-3.00)	3.34 (3.09-3.64)	4.28 (3.95-4.66)	5.08 (4.68-5.52)	6.29 (5.75-6.83)	7.34 (6.66-7.96)	8.51 (7.64-9.23)	9.81 (8.71-10.7)	11.8 (10.3-12.8)	13.4 (11.6-14.7)
2-day	3.21 (2.95-3.52)	3.89 (3.57-4.26)	4.96 (4.55-5.45)	5.86 (5.35-6.42)	7.18 (6.52-7.87)	8.31 (7.49-9.09)	9.53 (8.53-10.4)	10.9 (9.62-11.9)	12.8 (11.2-14.2)	14.5 (12.5-16.1)
3-day	3.40 (3.13-3.72)	4.11 (3.78-4.51)	5.23 (4.80-5.73)	6.16 (5.63-6.74)	7.50 (6.82-8.20)	8.64 (7.81-9.45)	9.86 (8.85-10.8)	11.2 (9.94-12.3)	13.1 (11.5-14.5)	14.7 (12.7-16.3)
4-day	3.59 (3.30-3.93)	4.34 (4.00-4.75)	5.50 (5.05-6.02)	6.45 (5.91-7.05)	7.83 (7.13-8.54)	8.97 (8.12-9.80)	10.2 (9.17-11.1)	11.5 (10.3-12.6)	13.4 (11.8-14.8)	15.0 (13.0-16.6)
7-day	4.22 (3.92-4.57)	5.07 (4.70-5.49)	6.30 (5.83-6.82)	7.31 (6.76-7.92)	8.76 (8.05-9.49)	9.97 (9.10-10.8)	11.3 (10.2-12.2)	12.6 (11.3-13.7)	14.6 (12.9-16.0)	16.2 (14.2-17.8)
10-day	4.81 (4.49-5.18)	5.74 (5.36-6.18)	7.03 (6.55-7.57)	8.09 (7.51-8.70)	9.57 (8.85-10.3)	10.8 (9.92-11.6)	12.1 (11.0-13.0)	13.4 (12.1-14.5)	15.3 (13.7-16.7)	16.9 (14.9-18.4)
20-day	6.49 (6.12-6.90)	7.71 (7.26-8.19)	9.19 (8.65-9.77)	10.4 (9.74-11.0)	12.0 (11.2-12.7)	13.2 (12.3-14.0)	14.4 (13.4-15.4)	15.7 (14.5-16.8)	17.4 (15.9-18.7)	18.7 (17.0-20.1)
30-day	8.09 (7.67-8.54)	9.56 (9.07-10.1)	11.2 (10.6-11.8)	12.4 (11.7-13.1)	14.0 (13.2-14.8)	15.2 (14.3-16.1)	16.4 (15.4-17.4)	17.6 (16.4-18.6)	19.1 (17.7-20.3)	20.2 (18.6-21.5)
45-day	10.3 (9.80-10.8)	12.1 (11.5-12.7)	14.0 (13.3-14.7)	15.4 (14.6-16.1)	17.2 (16.3-18.0)	18.5 (17.5-19.5)	19.8 (18.7-20.8)	21.0 (19.8-22.2)	22.6 (21.1-23.9)	23.7 (22.1-25.2)
60-day	12.3 (11.8-12.9)	14.5 (13.8-15.1)	16.5 (15.8-17.3)	18.1 (17.2-18.9)	20.0 (19.0-20.9)	21.4 (20.3-22.4)	22.7 (21.5-23.8)	23.9 (22.6-25.1)	25.4 (23.9-26.7)	26.4 (24.8-27.9)

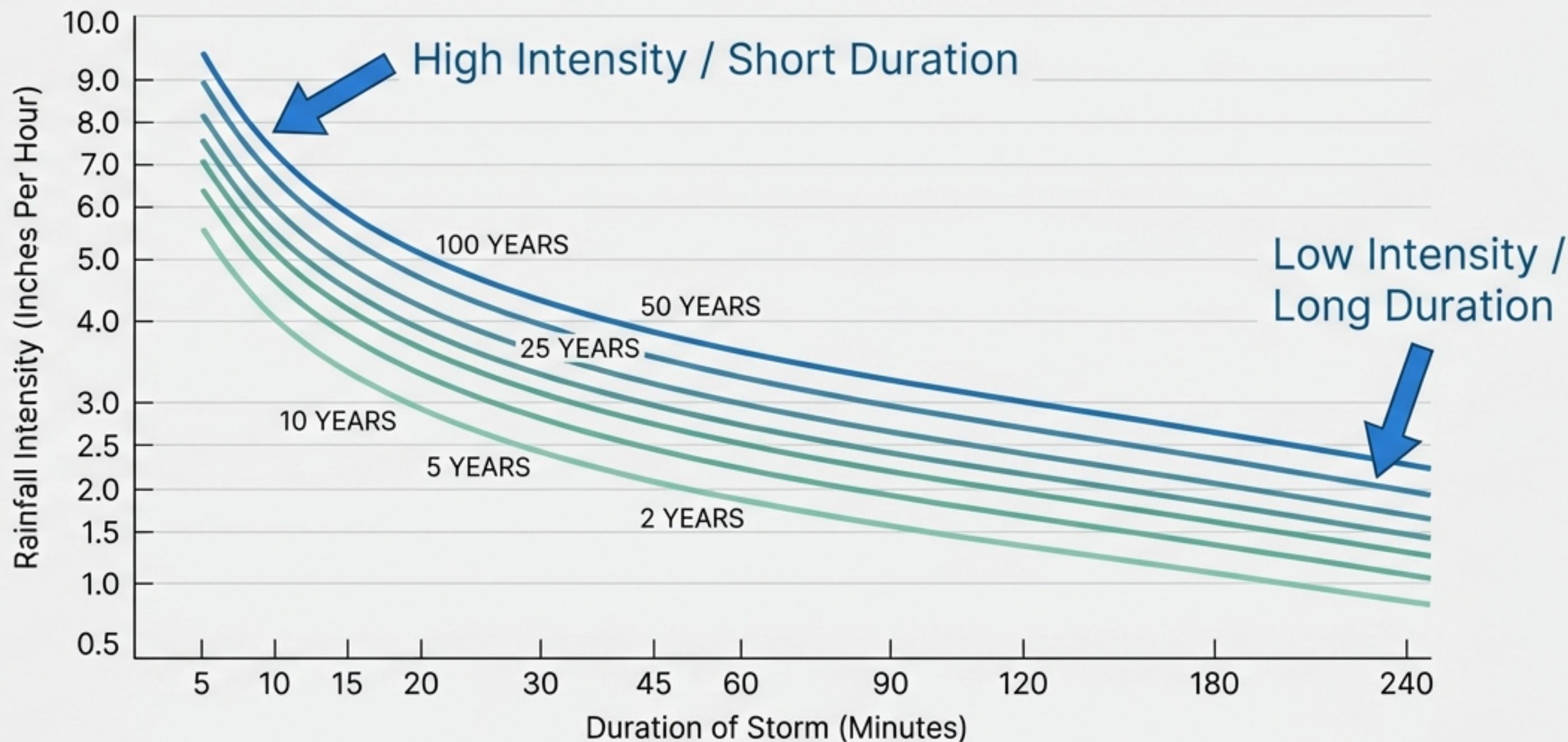
Note: The replaced table with correct values.



**The Gold Standard:**  
NOAA Atlas 14 is  
the authoritative  
source for  
precipitation  
frequency  
estimates.

**Key Concept:** A “100-year storm” doesn't happen every 100 years; it has a 1% chance of occurring in any given year.

# The IDF Curve: Intensity-Duration-Frequency



**Key Insight:** Rainfall intensity is inversely proportional to duration. A 5-minute burst is far more intense than a 24-hour drizzle. This relationship dictates how we design pipes and basins.

# Effective Precipitation: What Actually Runs Off?

$$P_e = P - \text{Losses}$$

$P_e$  = Effective Precipitation  
(Runoff Depth)

$P$  = Total Rainfall

Interception, Depression Storage,  
Infiltration, Evaporation

## Method 1: The Rational Method

Used for peak discharge ( $Q_p$ ) in small areas.

## Method 2: The NRCS (SCS) Curve Number Method

Used for volume and flow in larger, complex watersheds.

# Method 1: The Rational Method

$$Q_p = C_i A$$

Diagram illustrating the Rational Method formula:

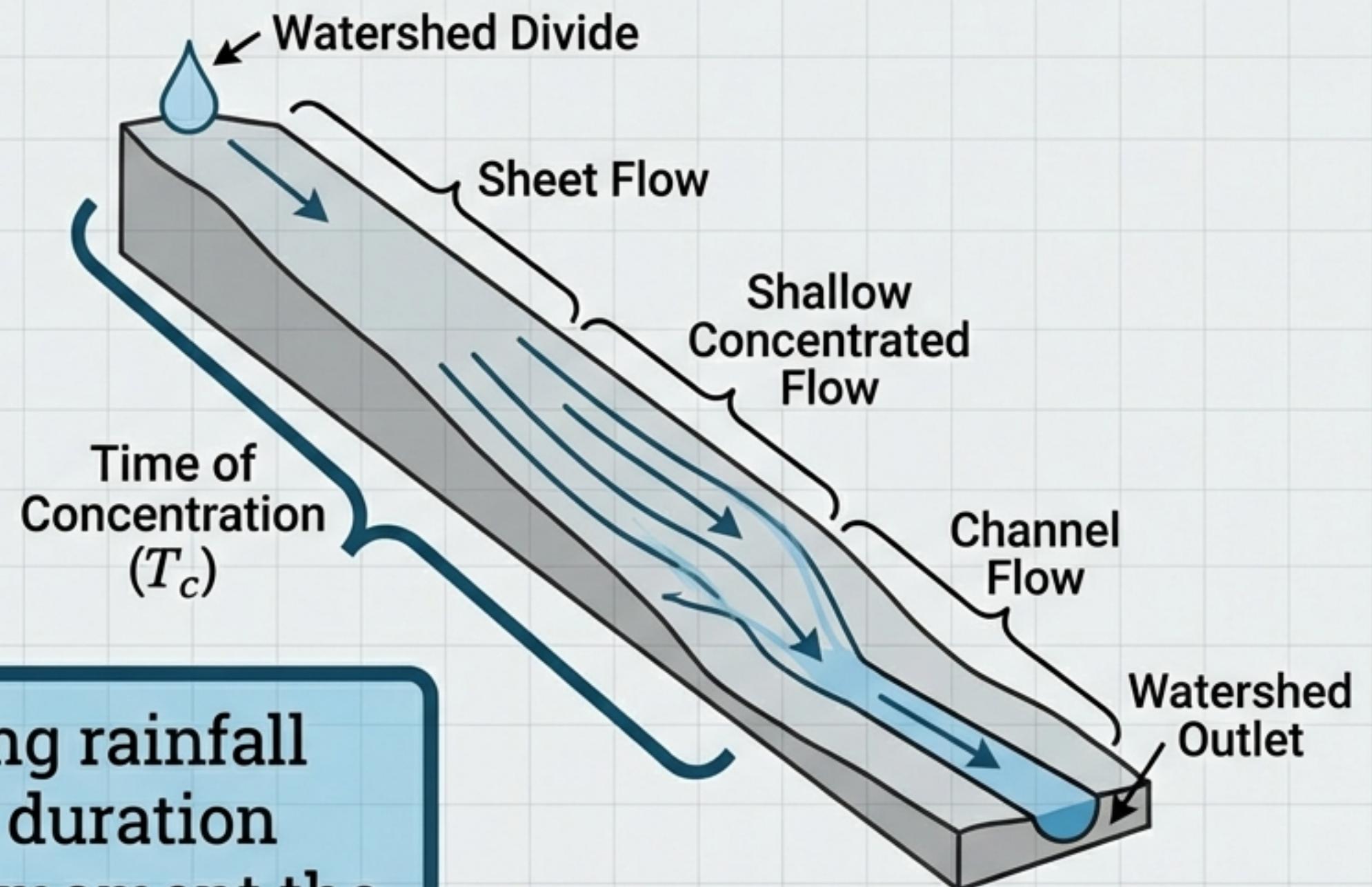
- Peak Discharge ( $cfs$ ):** Points to the variable  $Q_p$ .
- Runoff Coefficient (dimensionless):** Points to the variable  $C_i$ . Subtext: "surface impermeability".
- Rainfall Intensity (in/hr):** Points to the variable  $A$ .
- Drainage Area (acres):** Points to the variable  $A$ .

**Typical Runoff Coefficients**

Description of Area	Runoff Coefficient
Business: Downtown areas	0.70–0.95
Business: Neighborhood areas	0.50–0.70
Residential: Single-family areas	0.30–0.50
Residential: Multiunits, attached	0.60–0.75
Residential: Residential, suburban	0.25–0.40
Industrial: Light areas	0.50–0.80
Parks, cemeteries	0.10–0.25
Pavement: Asphalt or concrete	0.70–0.95
Roofs	0.75–0.95
Lawns, sandy soil: Flat, 2%	0.05–0.10
Lawns, sandy soil: Average, 2%–7%	0.10–0.15
Lawns, heavy soil: Flat, 2%	0.13–0.17
Source: ASCE (1992).	

# Critical Parameter: Time of Concentration ( $T_c$ )

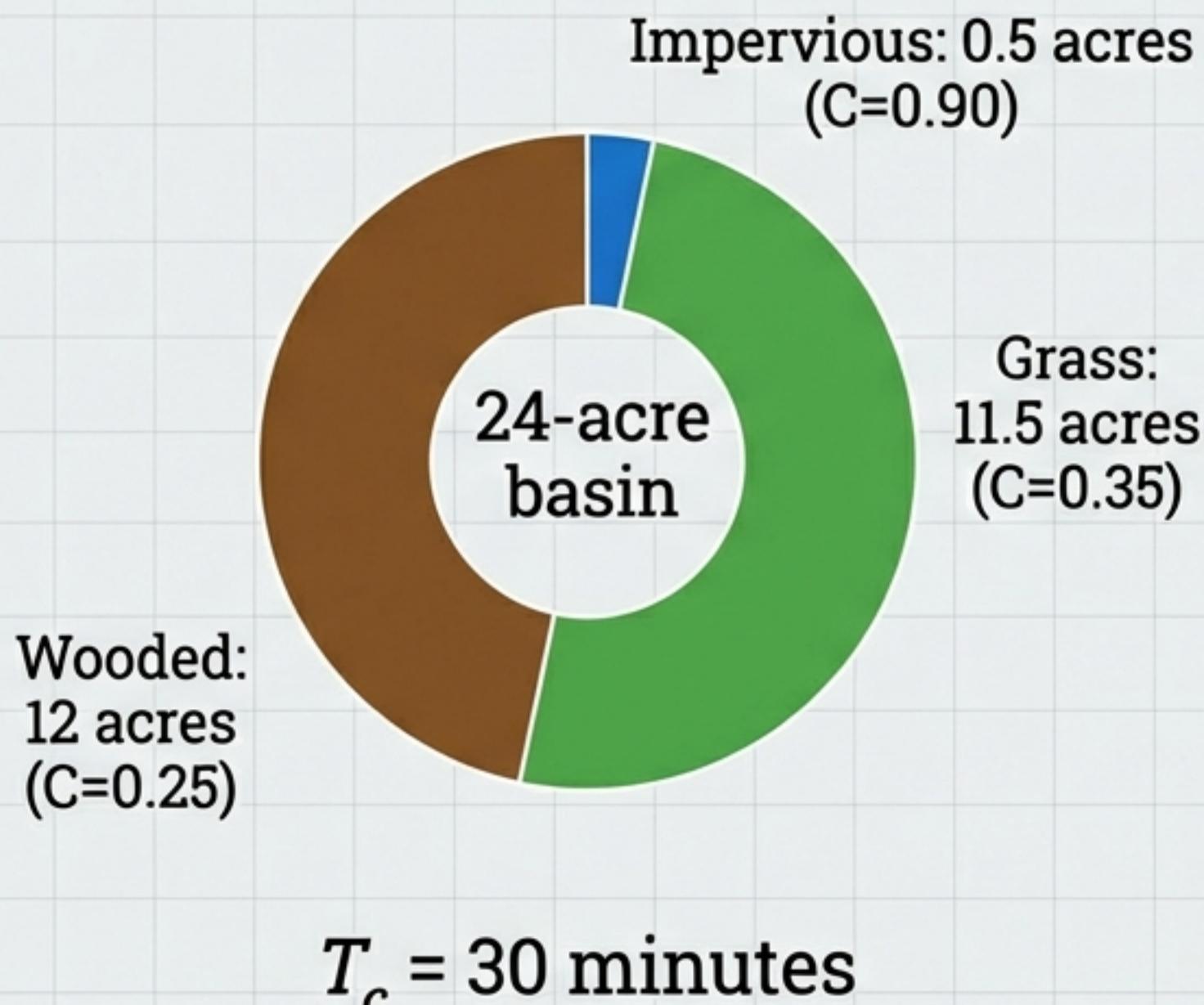
**Definition:** The longest time required for a drop of water to travel from the most remote point of the watershed divide to the watershed outlet.



**Design Rule:** When determining rainfall intensity ( $i$ ), we set the storm duration equal to  $T_c$ .  $T_c$  represents the moment the entire basin contributes to the flow.

# Case Study: Rational Method in Action

## The Scenario



## The Calculation

### Step 1. Weighted C Calculation

$$\text{Composite } C = \frac{(0.9 \times 0.5) + (0.35 \times 11.5) + (0.25 \times 12)}{24} = 0.31$$

### Step 2: Determine Intensity ( $i$ )

From IDF Curve @ 30 min duration:

$$i = 3.7 \text{ in/hr}$$

### Step 3: Calculate Peak Discharge ( $Q_p$ )

$$Q_p = 0.31 \times 3.7 \times 24 = 27.5 \text{ cfs}$$

# Method 2: The NRCS (SCS) Curve Number Method

Calculating Volume based on Soil and Land Use

Instead of a simple “C”, we use a Curve Number (CN) derived from Land Use + Hydrologic Soil Group.

- Soil Group A: High infiltration (Sand)
- Soil Group D: Low infiltration (Clay)

Potential Maximum Retention:

$$S = 1000/CN - 10$$

Effective Runoff:

$$Pe = (P - 0.2S)^2 / (P + 0.8S)$$

	Runoff Curve Numbers				
	Soil Group				
	A	B	C	D	
Open space (lawns, parks, etc.)					
Poor condition	68	79	86	89	
Fair condition	49	69	79	84	
Good condition	39	61	74	80	
Residential districts by average lot size					
1/8 acre or less	77	85	90	92	
1/4 acre	61	75	83	87	
1/3 acre	57	72	81	86	
1/2 acre	54	70	80	85	
1 acre	51	68	79	84	
2 acres	46	65	77	82	

# Case Study: NRCS Method in Action

400-acre basin, Middlesex, NJ. Soil Group B. Rainfall (P) = 6.36 inches.

## Step 1: Calculate Weighted Curve Number

Based on mixed land use (Impervious, Wooded, Meadow, Residential),  
the weighted average CN is determined to be **61.7**.



## Step 2: Calculate Potential Retention (S)

$$S = \frac{1000}{61.7} - 10 = \mathbf{6.21 \text{ inches}}$$

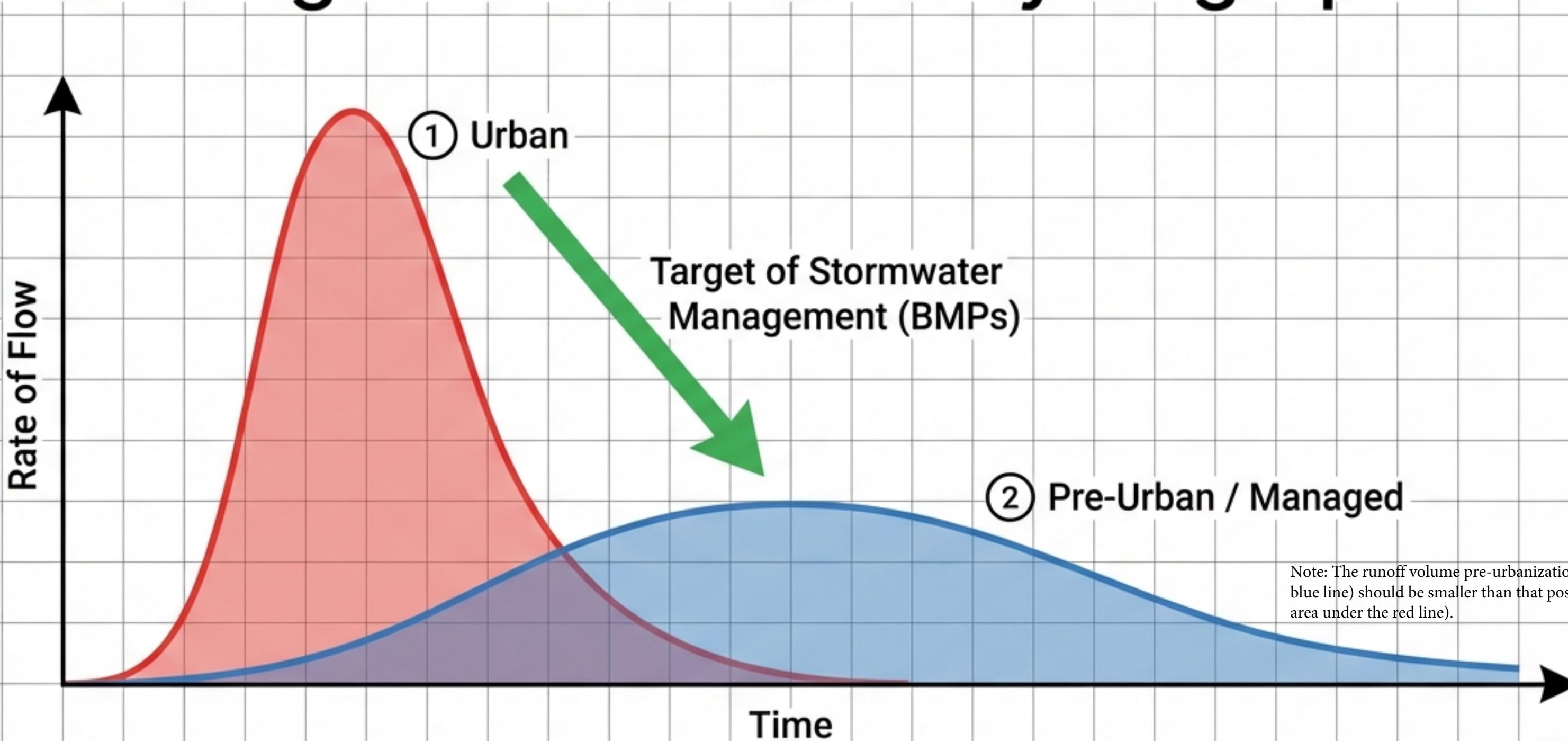


## Step 3: Calculate Effective Runoff (Pe)

$$P_e = \frac{(6.36 - 0.2(6.21))^2}{6.36 + 0.8(6.21)} = \mathbf{2.31 \text{ inches}}$$

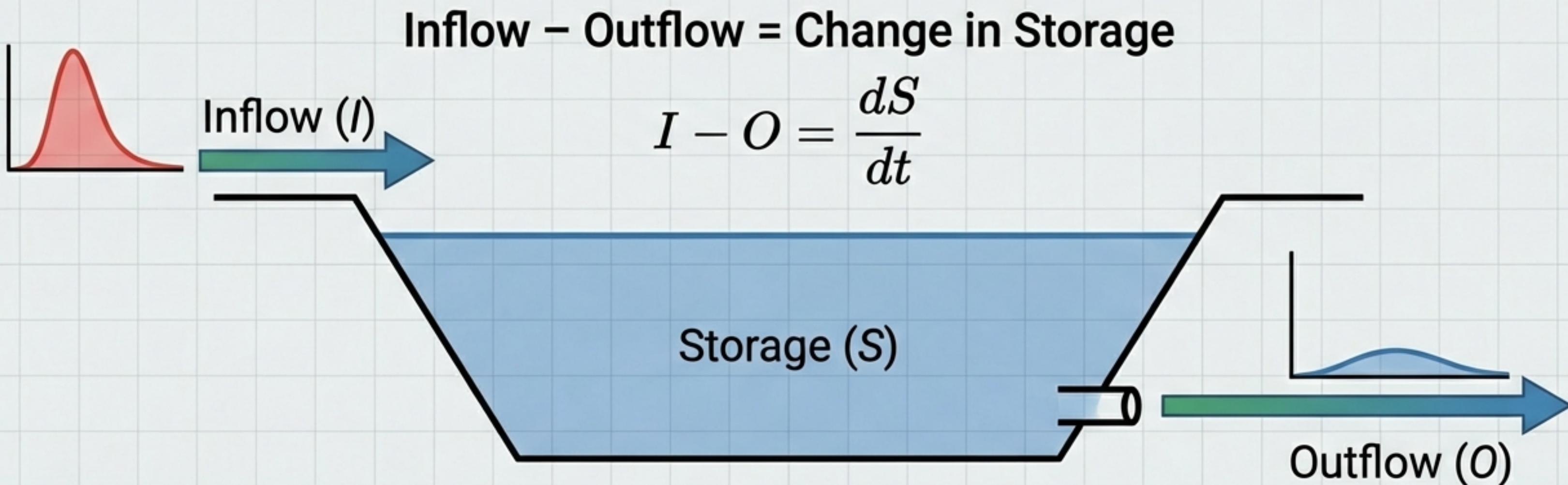
Result: Out of 6.36 inches of rain, the soil absorbs ~4 inches. The infrastructure must handle the remaining 2.31 inches of runoff.

# Visualizing the Storm: The Hydrograph



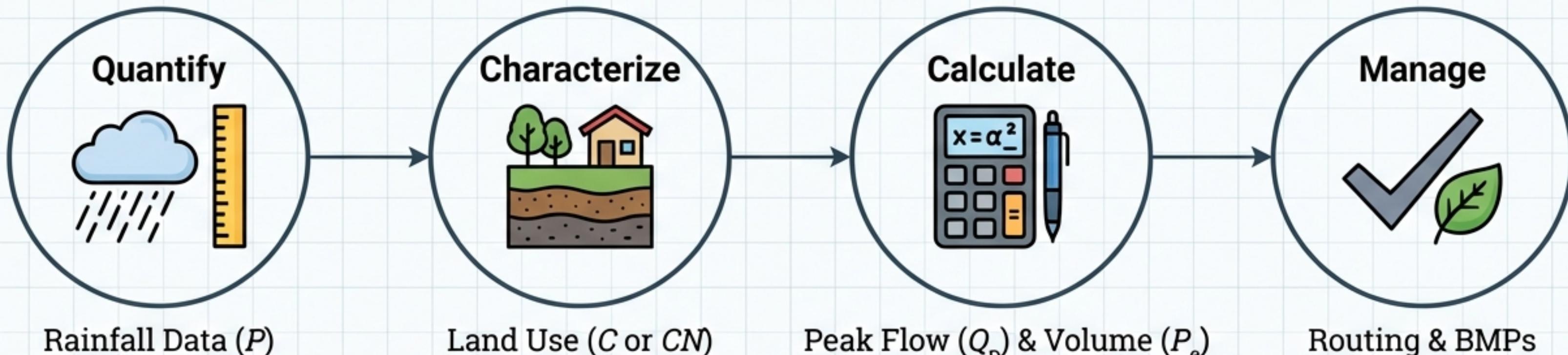
# Hydrologic Routing: Managing the Flow

We use detention basins to flatten the hydrograph. This process is modeled using the “Level Pool Routing” method.



The volume of inflow (the area under the red line) should be equal to the volume of outflow (the area under the blue line) if no water is lost from the storage basin (e.g., exfiltration)

# Summary: The Hydrologic Design Cycle



Effective stormwater design is not just about moving water away—it's about restoring the natural balance to protect our communities and environment.