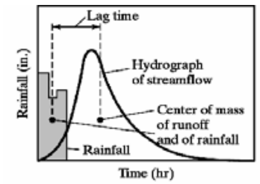
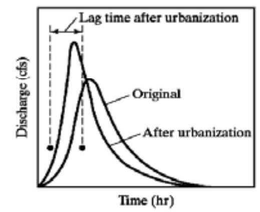
Urban Hydrology - Storm Sewer Design

Characteristics of urban watersheds

Urban watersheds have
- high percentage of impervious areas
- man-made drainage infrastructure

Effect of urbanization:
- Faster response time
- Larger runoff volumes
- Larger peak flows





Design of storm sewers

Storm sewers must be designed to avoid surcharge.

Design decisions
- **dimension of pipes**
- **spacing of inlets**
- **slope of pipes**

Design procedure:
- Assume design return period
- Derive critical duration of rainfall for each inlet
- Determine intensity of rain from IDF (Intensity Duration Frequency) curves
- Estimate peak discharge at each inlet
- Route flow through sewer accumulating the contribution from each inlet.

Estimation of sewer capacity

The capacity of a sewer pipe to convey water is a function of
- Diameter
- Slope
- Surface roughness

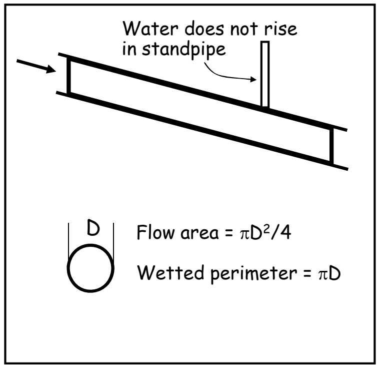
Manning's formula

$$V = \frac{Q}{A} = \frac{1.49}{n} R^{2/3} \sqrt{S}$$

Q: discharge [cfs]
A: flow area [ft^2]
V: average velocity [ft/s]
S: slope [ft/ft]
R: hydraulic radius [ft]
n: roughness coefficient

Hydraulic radius for sewer pipe

Design condition: sewer is flowing full under gravity, not pressurized flow.



Hydraulic radius for full pipe:

$$R = \frac{\text{Flow area}}{\text{Wetted perimeter}}$$

$$= \frac{\pi D^2/4}{\pi D} = \frac{D}{4}$$

Manning's roughness

Material	Manning's coefficient n
Brick	0.015
Cast-iron, new	0.012
Concrete	
Steel forms	0.011
Wooden forms	0.015
Sewer	0.013
Corrugated metal	0.024

Calculation of discharge in sewer pipe

Example 1

What is the discharge in a 2-ft concrete sewer pipe flowing full (unpressurized), with a 1% slope.

Solution:

$n = 0.013$

$S = 0.01$

$R = D/4 = 0.5$

$A = \pi D^2/4 = 3.14$

$$V = \frac{Q}{A} = \frac{1.49}{n} R^{2/3}\sqrt{S} \quad \Rightarrow \quad Q = \frac{1.49}{n} A R^{2/3}\sqrt{S} = 14.3 \text{ cfs}$$

Pipe sizing with Manning's formula

Example 2

A concrete sewer must be constructed on a 1.75% grade to convey a design discharge of 25 cfs. Determine the diameter of the sewer pipe.

Solution:

$$Q = \frac{1.49}{n} A R^{2/3}\sqrt{S}$$

$$= \frac{1.49}{n}\left(\frac{\pi D^2}{4}\right)\left(\frac{D}{4}\right)^{2/3}\sqrt{S}$$

$$= \frac{0.464}{n} D^{8/3}\sqrt{S}$$

$$D = \left(\frac{2.16\,Q\,n}{\sqrt{S}}\right)^{3/8}$$

$$D = \left(\frac{2.16 \times 25 \times 0.013}{\sqrt{0.0175}}\right)^{3/8}$$

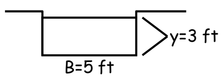
$$= 1.87 \approx 2 \text{ ft}$$

Flow velocity in rectangular channel

Example 3

Determine the average velocity in a full-flowing rectangular channel that is 5 feet wide, 3 feet deep, and that has a slope of 0.5%. The Manning roughness is 0.019.

Solution:



Hydraulic radius:

Wetted perimeter = B+2y
Area = By
R = By / (B+2y)

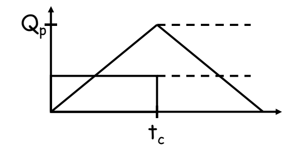
$$V = \frac{1.49}{n} R^{2/3} \sqrt{S}$$

$$= \frac{1.49}{n} \left(\frac{by}{b+2y} \right)^{2/3} \sqrt{S}$$

$$= \frac{1.49}{0.019} \left(\frac{5 \times 3}{5 + 2 \times 3} \right)^{2/3} \sqrt{0.005}$$

$$= 8.9 \text{ ft/s}$$

The Rational Method



State of equilibrium:

Rate of input = rate of output

Peak flow is reached when the watershed is in equilibrium.

$$Q_p = I_{excess}\ A = CIA$$

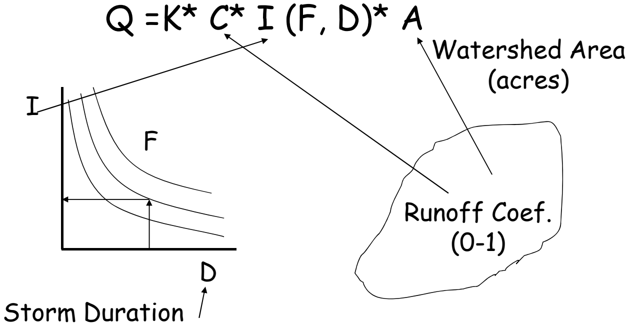
Note that if I is in [in/hr] and A is in ac, then Q_p is in cfs.

$$1 \text{ ac-in/hr} \times \frac{(43{,}560 \text{ ft}^2/\text{ac})(1/12 \text{ ft/in})}{(3600 \text{ sec/hr})} = 1.008 \text{ cfs}$$

The Rational Method

1.008 (CONVERSION FACTOR)

$$Q = K^* \ C^* \ I\ (F, D)^* \ A$$



Good for watershed < 200 acres

Runoff Coefficients for 2 Yr to 10 Yr Frequency design

Description of the Area	Runoff Coefficients
Buisness	
Downtown areas	0.70-0.95
Neighborhood areas	0.50-0.70
Residential	
Single family areas	0.30-0.50
Multi-units, detached	0.40-0.60
Multi-units, attached	0.60-0.75
Residential (suburban)	0.25-0.40
Apartment dwelling areas	0.50-0.70
Industrial	
Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.35
Railroad yard areas	0.20-0.40
Unimproved areas	0.10-0.30

Application

1. Determine the return period (based on the type of hydraulic structure to be built)

2. Calculate the time of concentration of the watershed.

3. Set the design storm duration equal to the time of concentration and determine the storm intensity from IDF curves relevant to the site.

4. Determine the watershed area in acres.

5. Determine a weighted runoff coefficient.

6. Determine the design peak discharge.

Runoff coefficient for nonhomogeneous areas

An urban watershed has the following characteristics:

Land use	Area
Single family areas	30 ac
Commercial	3 ac
Park	7 ac

Determine the runoff coefficient for the area.

Solution

From table 6.6.

Land use	C
Single family areas	0.40
Commercial	0.60
Park	0.15

$$\overline{C} = \frac{30\times 0.40 + 3\times 0.60 + 7\times 0.15}{30+3+7}$$

$$= 0.37$$

Determine the 10-yr peak flow at a stormwater inlet in Tallahassee, Florida. The watershed is a 40-ha area in rolling terrain. An inlet time (t_c) of 20 min may be assumed. Land use is as follows:

Land use	Area	C
Single family	30 ha	0.40
Commercial	3 ha	0.60
Parks	7 ha	0.15

Q = CIA = 0.37*5.6in/hr*40acres = 82.9cfs

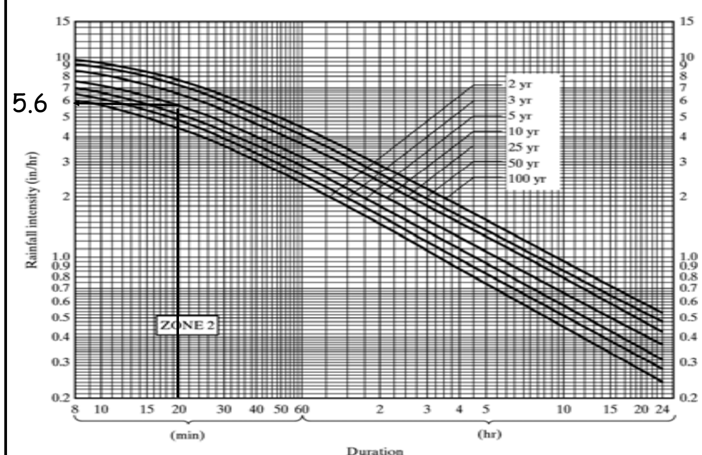


Figure 6.5

IDF curves for the Tallahassee, Florida, region. (From Weldon, 1985.)

Time of Concentration (TOC)

Time of Concentration is often defined as the time required for wave (water) to travel from hydrologically most remote point in the basin (watershed) to the basin (watershed) outlet.

Time required for all parts of a basin to contribute to discharge at outlet simultaneously

Time of concentration represents the hydrologic response time of watershed.

Time of concentration

Factors affecting t_c:

- Surface roughness
- Slope
- Travel length

Many empirical formula available for calculating t_c.

Time of concentration can be calculated as

$$t_c = L/V$$

where L is travel distance and V is flow velocity (wave?).

Calculate several possible flow paths, and use the one that gives the longest travel time

Time of Concentration (TOC)

- Lumped Approach – ONE EQUATION FOR WATERSHED
  - Kirpich Equation
  - SCS Lag Method
- Disagreggated Approach – SPLIT INTO TWO/THREE
  - Overland Flow
    - Kinematic Wave Equation
    - SCS Nomograph Method
  - Gutter Flow
    - SCS Nomograph Method
  - Channel/Pipe Flow
    - Manning's Equation

LUMPED APPROACH
Time of concentration by the Kirpich Equation

$$t_c = 0.0078 L^{0.77} S^{-0.385}$$

where

t_c : time of concentration [min]
L : length of channel/ditch from headwater to outlet [ft]
S: average watershed slope [ft/ft]

For overland flow on concrete channels, multiply tc by 0.4
For concrete channels multiply by 0.2

LUMPED APPROACH
Time of concentration by the Kirpich Equation

Find the time of concentration of a watershed with slope 0.006. The maximum length of travel of water for this watershed is 950 m.

Slope = 0.006.
Length of the channel = 950 m
= 950 (3.281 ft/m) = 3116.8 ft

$$t_c = 0.0078 L^{0.77} S^{-0.385}$$

$= 0.0078\ (3116.8)^{0.77}\ (0.006)^{-0.385}$

$= 27.4$ min.

LUMPED APPROACH
Time of concentration by the SCS Lag method

Lag time = $t_p = \dfrac{L^{0.8}(S+1)}{1900\sqrt{y}}$

where

- t_p : lag time [hr]
- L : length to divide [ft]
- y : average watershed slope [%]
- S = 1000 / CN –10 [in]
- CN : curve number

Time of concentration: $t_c = 1.67\ t_p$ [hr]

Example: Time of concentration by SCS Lag Method

A storm sewer inlet collects flow from a with the following characteristics:

- Area = 2 ac.
- Land use: residential, average lot size of ¼ ac.
- Soil type: clay loam (SCS soil group C).
- 15% of the watershed is a paved road.
- Average slope of the watershed is 1%.
- The length of the watershed is 400 ft.

Determine the time of concentration for the watershed.

Solution:

CN for Soil Group C, ¼ ac lots = 83

CN for Soil Group C, paved road = 98

Weighted CN = 0.85×83 + 0.15×98 = 85

$$S = \frac{1000}{CN} - 10 = \frac{1000}{85} - 10 = 1.76 \text{ in}$$

$$t_p = \frac{L^{0.8}(S+1)}{1900\sqrt{y}} = \frac{400^{0.8}(1.76+1)}{1900\sqrt{1}} = 0.175 \text{ hr}$$

$$t_c = 1.67 t_p = 1.67 \times 0.175 \text{ hr} = 0.292 \text{ hr} \approx \boxed{17 \text{ min}}$$

Disaggregated Approach
Overland Flow & Gutter Flow

SCS Nomograph Method

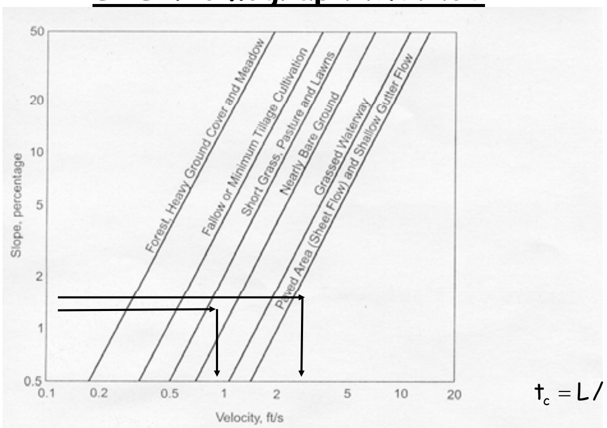


Figure 2-11: Average Overland Flow Velocities as a Function of Land Use Characteristics and Surface Slope

$t_c = L/V$

Disaggregated Approach - Channel Flow

Manning's Equation

Open channels are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geological Survey (USGS) quadrangle sheets. Manning's equation or water surface profile information can be used to estimate average flow velocity. Average flow velocity is usually determined for bank-full elevation.

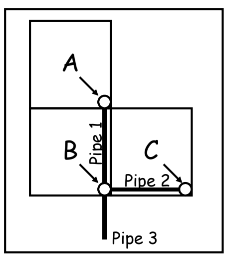
Manning's equation is:

$$V = \frac{1.49 r^{\frac{2}{3}} s^{\frac{1}{2}}}{n}$$

V = average velocity (ft/s)
r = hydraulic radius (ft) and is equal to a/p_w
a = cross sectional flow area (ft^2)
p_w = wetted perimeter (ft)
s = slope of the hydraulic grade line (channel slope, ft/ft)
n = Manning's roughness coefficient for open channel flow.

$t_c = L/V$

Sewer design with Rational Method



Use the Rational Method to size each pipe in the network for the 25-yr peak discharge. (Size each pipe assuming full flow)

Assume concrete pipes with n=0.013

Basin characteristics

Basin	Area [ac]	C	t_c [min]
A	6.0	0.6	20
B	4.0	0.8	10
C	4.5	0.8	15

Pipe characteristics

Pipe	Length [ft]	Slope [%]
1	500	1.0
2	400	1.2
3	500	0.9

I-D-values for 25-yr storm

Duration [min]	Intensity [in/hr]
5	8.40
10	7.02
15	5.96
20	5.26
30	4.42
60	2.97

Solution:

Pipe 1: Runoff from subbasin A

Storm duration: $D=t_c$=20 min

Storm intensity: I_{20} = 5.26 in/hr

Peak flow: $Q_p = CIA = 0.6(5.25)(6.0) = 19$ cfs

Manning's formula: $D = \left(\frac{2.16\,Q\,n}{\sqrt{S}}\right)^{3/8} = \left(\frac{2.16\,(19)\,(0.013)}{\sqrt{0.01}}\right)^{3/8}$

$= 1.87\text{ ft} \approx \boxed{2\text{ ft}}$

Average velocity in pipe 1: $V = \frac{Q}{A} = \frac{Q}{\pi D^2/4} = \frac{19\text{ cfs}}{3.14\text{ ft}^2} = 6.1\text{ ft/s}$

Travel time in pipe 1: t = L/V = 500/6.1 = 82 sec = 1.4 min

<u>Pipe 2</u>: Runoff from subbasin C

Storm duration: D=t_c=15 min

Storm intensity: I_{15} = 5.96 in/hr

Peak flow: Q_p = CIA = 0.8(5.96)(4.5) = 21.5 cfs

Manning's formula: $D = \left(\frac{2.16\,Q\,n}{\sqrt{S}}\right)^{3/8} = \left(\frac{2.16\,(21.5)\,(0.013)}{\sqrt{0.012}}\right)^{3/8}$

$= 1.89 \text{ ft} \approx \boxed{2 \text{ ft}}$

Average velocity in pipe 2: $V = \frac{Q}{A} = \frac{Q}{\pi D^2/4} = \frac{21.5 \text{ cfs}}{3.14 \text{ ft}^2} = 6.8 \text{ ft/s}$

Travel time in pipe 2: t = L/V = = 400/6.8 = 59 sec $\approx$ 1 min

<u>Pipe 3</u>: Runoff from all three subbasins

Area: 14.5 ac

Runoff coefficient: $\bar{C} = \frac{6(0.6) + 4(0.8) + 4.5(0.8)}{14.5} = 0.72$

Time of concentration:

$$t_c = \max\begin{cases} t_c \text{ for subbasin B} \\ t_c \text{ for subbasin } A + \text{travel time in pipe 1} \\ t_c \text{ for subbasin } C + \text{travel time in pipe 2} \end{cases}$$

$$= \max\begin{cases} 10 \text{ min} \\ 20 + 1.4 = 21.4 \text{ min} \\ 15 + 1 = 16 \text{ min} \end{cases}$$

$$= 21.4 \text{ min}$$

Storm duration: D=t_c=21.4 min

Storm intensity: $I_{21.4}$ = 5.14 in/hr (interpolation)

Peak flow: Q_p = CIA = 0.72(5.14)(14.5) = 53.7 cfs

Manning's formula: $D = \left(\frac{2.16\,Q\,n}{\sqrt{S}}\right)^{3/8} = \left(\frac{2.16\,(53.7)\,(0.013)}{\sqrt{0.009}}\right)^{3/8}$

$= 2.82 \text{ ft} \approx \boxed{3 \text{ ft}}$

GROUND WATER

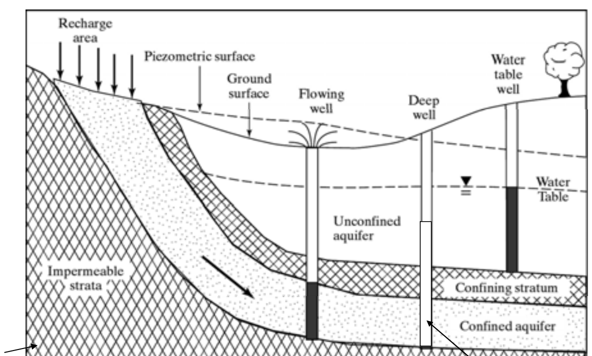


Figure 8.6

Schematic cross section illustrating unconfined and confined aquifers.

Darcy's Law

In the mid-1800s the French engineer Henry Darcy successfully quantified several factors controlling ground water movement. These factors are expressed in an equation that is commonly known as Darcy's Law.

$$Q = -KA\left(\frac{dh}{dl}\right)$$

Note: Q = discharge (volume of water per unit time)
K = hydraulic conductivity (dependent upon size and arrangement of pores, and fluid dynamics such as viscosity, density and gravitational effects)
A = cross-sectional area (at a right angle to ground water flow direction)
dh/dl = hydraulic gradient (this is the common notation for a change in head per unit distance)

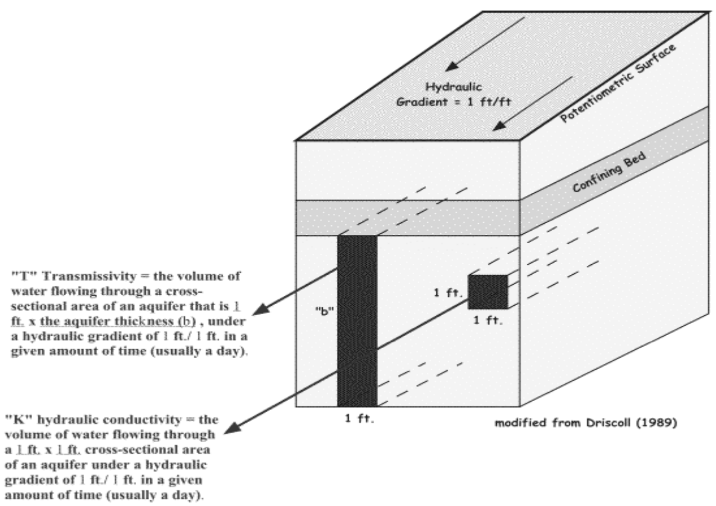
Hydraulic Conductivity

The coefficient of proportionality between the flow rate in an aquifer and the energy gradient causing that flow:

$$q = Ki$$

where q = discharge per unit area
i = hydraulic gradient dh/l
K = hydraulic conductivity

Hydraulic conductivity has units of ft/day, m/day, gpd/ft^2



Transmissivity

A measure of the capability of an aquifer to transmit water through its entire thickness.

$$T = \overline{K}b$$

where T = Transmissivity (L^2T^{-1})
$\overline{K}$ = average conductivity (LT^{-1})
b = aquifer thickness (L)

A term applied to confined Aquifers !!