1.1

Course Number: CE 365K
Course Title: Hydraulic Engineering Design
Course Instructor: R.J. Charbeneau

- Subject: ***Urban Drainage Systems***
- Topics Covered:
  1. Hydraulics of sheet flow (overland flow)
  2. Hydraulics of gutters and drainage inlets
  3. Design storm: estimating peak discharge
  4. Design of storm sewer systems

1.2

Urban Storm Drainage System

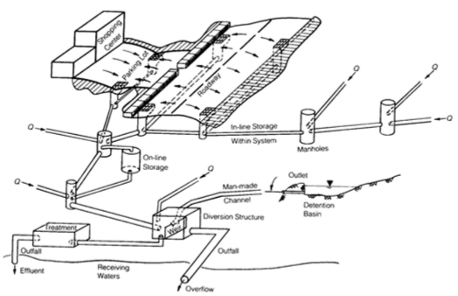


Figure 6.1—Principal hydraulic elements in urban storm drainage system.

ASCE, 1992

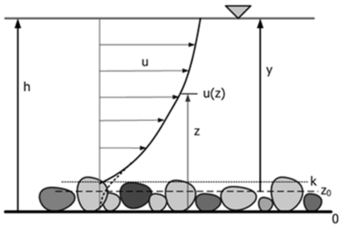
1.3

Topic 1 – Hydraulics of Sheet (Overland) Flow

- Overland flow as sheet flow
- Continuity equation for overland flow
- Determine "Time of Concentration" [equilibrium time]

1.4

Sheet Flow on a Rough Surface: Turbulent Boundary Layer



- $R_h \rightarrow y$

1.5

Manning Equation for Sheet Flow

$$\boxed{V = \frac{\phi}{n} R_h^{2/3} \sqrt{S_f}} \quad \rightarrow \quad \boxed{q = V\,y = \frac{\phi}{n} y^{5/3} \sqrt{S_f}}$$

q = "unit discharge" (L^2/T)

- Manning equation developed for open channel flow – how well does it work for sheet flow?
- Does rainfall impact the calculation of sheet flow discharge?

1.6

CRWR Research for TxDOT

(Highway Drainage through Superelevation Transitions)

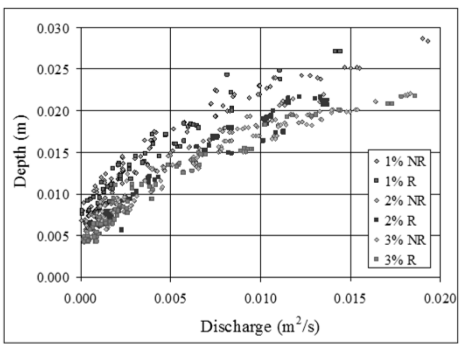
Rainfall Simulator Setup

1.7

CRWR Research for TxDOT

1.6

Typical Data:



No significant effect from simulated rainfall

1.9

Usual Approach for Sheet Flow Calculations in Engineering Design

- Use Manning equation

$$\boxed{q = \frac{\phi}{n}\, y^{5/3}\, S_o^{\ 1/2}}$$

S_o = slope of surface (pavement)

Sheet flow equation has the form

$$\boxed{q = \alpha\, y^{m}}$$

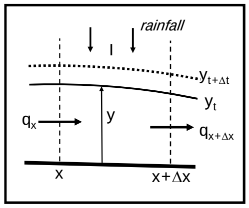
$\alpha = \phi\, S_o^{1/2} / n$

$m = 5/3$

Next step: add continuity

1.10

Continuity Equation



Per unit width, $q = v\, y$

Flow in – Flow out = Storage Increase

$(q_x + I\, \Delta x)\, \Delta t \;-\; (q_{x+\Delta x})\, \Delta t = (y_{t+\Delta t} - y_t)\, \Delta x$

For small Δx and Δt:

$$\boxed{\begin{aligned} q_{x+\Delta x} &= q_x + \frac{\partial q}{\partial x}\Delta x \\ y_{t+\Delta t} &= y_t + \frac{\partial y}{\partial t}\Delta t \end{aligned}}$$

Continuity Equation for Overland Flow:

$$\boxed{\frac{\partial y}{\partial t} + \frac{\partial q}{\partial x} = I}$$

Both y and q are variables

1.11

Kinematic Wave Theory

Express flow (q) as a function of the storage (y)

Manning equations can be written:

$$\boxed{q = \alpha\, y^{5/3} \quad \leftrightarrow \quad V = q/y = \alpha\, y^{2/3}}$$

The continuity equation becomes

$$\boxed{\frac{\partial y}{\partial t} + \left(\frac{dq}{dy}\right)\frac{\partial y}{\partial x} = I}$$

Now only y is a variable

Wave celerity:

$$\boxed{c = c(y) = \frac{dq}{dy} = \frac{5}{3}\alpha\, y^{2/3} = \frac{5}{3}V}$$

<u>Conclusion</u>: the drainage wave moves faster than the water!!

1.12

Method of Characteristics

Continuity equation

$$\boxed{\frac{\partial y}{\partial t} + \left(\frac{dq}{dy}\right)\frac{\partial y}{\partial x} = I}$$

First-order (hyperbolic) PDE

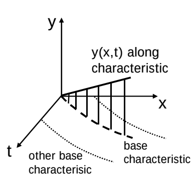
$\longleftrightarrow$

MOC formulation

$$\boxed{\frac{dt}{1} = \frac{dx}{dq/dy} = \frac{dy}{I}}$$

Equivalent system of ODEs; one set of ODEs applies along each "characteristic"

Calculate solution along "drainage path"



1.13

Application to Overland Flow

Constant "rainfall excess" I_o starting at time 0

$$\boxed{\frac{dy}{dt}=I_o \quad\rightarrow\quad y=I_o(t-t_o)}$$

$$\boxed{\frac{dx}{dt}=c(y)=\frac{5}{3}\alpha y^{2/3}=\frac{5}{3}\alpha\left(I_o(t-t_o)\right)^{2/3} \quad\rightarrow\quad x=x_o+\alpha I_o^{2/3}(t-t_o)^{5/3}}$$

Drainage response time
(**<u>Time of Concentration</u>**, $\mathbf{T_c}$)
at x = L:

$$\boxed{T_c=\left(\frac{L}{\alpha I_o^{2/3}}\right)^{3/5}}$$

1.14

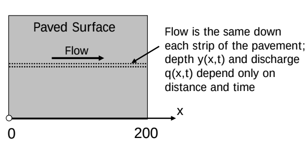
Example #1 - Runoff from Pavement Surface

Paved asphalt surface (n = 0.015)

Slope S = 0.01

Length L = 200 ft

Constant rainfall intensity I = 10 inch/hr (0.000231 ft/s).



$\alpha = \phi S^{1/2}/n$

$\alpha = 1.49\,(0.01)^{1/2}/0.015 = 10$

1.15

Questions:

1. What is the maximum discharge at edge of pavement (per unit width)?

   $q = I\,L = 0.000231$ ft/s * 200 ft = 0.0462 ft^2/s

2. How long does it take to reach this discharge (T_c)?

   $T_c = (L / (\alpha\, I^{2/3}))^{3/5} = (200 / (10 * 0.000231^{2/3}))^{3/5} = 172$ sec.

3. What is the maximum depth at edge of pavement?

   - Kinematic wave

     $y = I\,T_c = 0.000231$ ft/s * 172 sec = 0.0397 ft = 0.48 inch

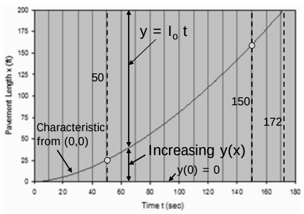
   - Manning equation

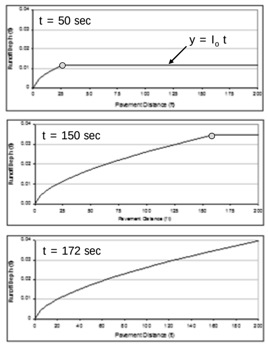
     $y = (q / \alpha)^{3/5} = (0.0462 / 10)^{0.6} = 0.0397$ ft

t_o

1.16

Example #1: Drainage Wave Profiles

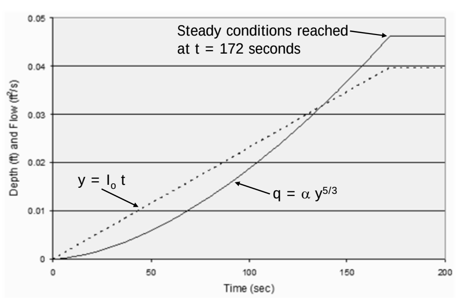




Drainage Depth Profiles at different times (50, 150, 172 seconds)

1.17

Example #1: Depth and Flow at Pavement Edge



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Conclusions

- Steady-state watershed response occurs at the Time of Concentration, T_c, which should be used as the design rainfall duration ($T_d = T_c$)

- Kinematic wave model for time of concentration (Manning Eq.):

$$T_c = \left[\frac{nL}{\phi S^{1/2} I_o^{2/3}}\right]^{3/5} = \frac{n^{0.6} L^{0.6}}{\phi^{0.6} S^{0.3} I_o^{0.4}}$$

Overland Flow

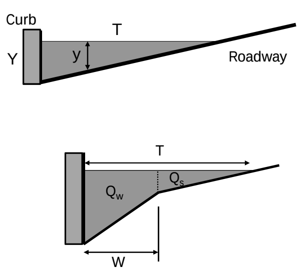
1.19

Topic 2 – Hydraulics of Gutters and Drainage Inlets

- Simple and composite gutters
- Curb inlets on grade
- Curb inlets in sag

1.20

Simple and Composite Gutter

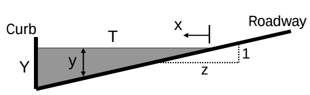


T = "spread"

Y = depth at curb

1.21

Simple Gutter Discharge (Izzard's Eq.)



Gutter longitudinal slope = S_o

Pavement cross-slope $S_x = 1/z = Y/T$

Area $A = (Y\ T)/2 = S_x T^2/2$

Wetted Perimeter $P = T\ (1 + S_x^2)^{0.5} + T\ S_x$

Typically $S_x \sim 0.02$ and $P = 1.020\ T \rightarrow P = T$

$$Q = \int_0^T y\,V(x)\,dx = \int_0^T y\left(\frac{\phi}{n} y^{2/3} S_o^{1/2}\right)dx = \frac{\phi\sqrt{S_o}}{n}\int_0^T (S_x x)^{5/3}\,dx = \frac{3}{8}\frac{\phi S_x^{5/3}\sqrt{S_o}}{n} T^{8/3}$$

Izzard, 1946

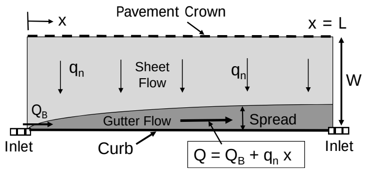
Izzard's equation for gutter flow:

$$\boxed{Q = \frac{3}{8}\frac{\phi}{n} S_x^{5/3}\sqrt{S_o}\,T^{8/3} = \frac{3}{8}\frac{\phi\sqrt{S_o}}{n S_x} Y^{8/3}}$$

1.22

Travel Time (T_c) in Gutters

- Lateral inflow (q_n) from pavement surface causes the gutter discharge to increase along the drainage length



Gutter Flow Travel Time: $T_c = \frac{4/3}{\alpha_g^{0.75} q_n}\left[Q_T^{0.75} - Q_B^{0.75}\right]$

$$\alpha_g = \frac{0.945\phi S_x^{1/\beta}\sqrt{S_o}}{n}$$

1.23

Drainage Inlets

- Types of inlets
- Performance of curb inlets
- Performance of depressed curb inlets
- Curb inlets in sag

1.24

Drainage Inlets

Curb inlets are used most often on urban streets and highways. These are usually depressed, and may also be recessed back from the curb.

Gutter (grate) inlets can be used on bridges, but have issues with safety (bicycles) and clogging.

Slotted drains can be used in parking lots to collect overland sheet flow.

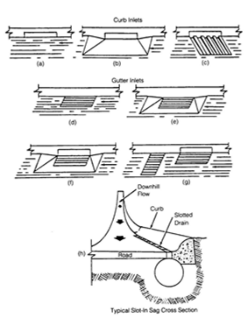


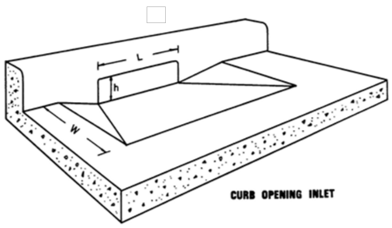
Figure 6.17—Stormwater inlets: (a) undepressed, (b) depressed, (c) deflector inlet, (d) undepressed, (e) depressed, (f) combination inlet—grate placed directly in front of curb opening depressed, (g) multiple inlet undepressed, and (h) slotted drain (AISI, 1985).

ASCE, 1992

1.25

Curb Inlets

Design questions: how does the capture and bypass of gutter discharge depend on inlet length L and inlet depression?



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Curb Inlets

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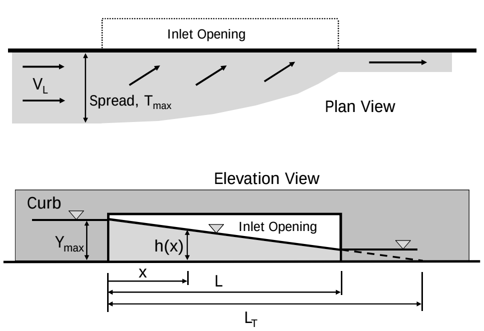
Analysis of Flow to Curb Inlets



1.28

Analysis of Curb Inlets (Izzard, 1950)

- The specific energy E is equal to the approach velocity head plus the curb depth Y: $E = Y + V_L^2/2g$. However, the approach velocity V_L does not contribute to flow entering the inlet.
- Only Y is significant in causing flow into the inlet. The edge of the inlet acts as a control point, and the flow at the inlet lip is critical (based on Y).

Critical flow: $y_c = (2/3)\,Y$ and $V_c^2/2\,g = (1/3)\,Y$

Unit discharge q based on curb depth Y:

$$q = y_c V_c = \left(\frac{2}{3}Y\right)\left(\sqrt{\frac{2\,g\,Y}{3}}\right) = \left(\frac{2}{3}\right)^{3/2}\sqrt{g}\,(Y)^{3/2}$$

1.29

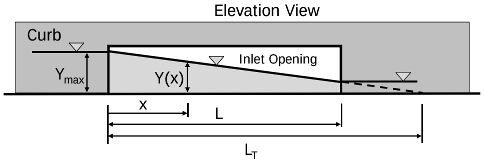
Variable Depth Along Inlet

Because of flow into the inlet, the depth of water will vary along the inlet opening. Izzard (1950) assumed that the hydraulic head varies linearly along the length of the inlet opening according to

$$Y = Y_{max}\,[1 - x/L_T]$$

L_T = theoretical length of the inlet for complete capture of gutter flow

Elevation View



1.30

Results

These assumptions with variable inlet depth give

$$Q_{CI} = \int_0^L y_c V_c\,dx = \int_0^L \left(\frac{2}{3}Y\right)\sqrt{\frac{2\,g\,Y}{3}}\,dx = \frac{2}{3}\sqrt{\frac{2\,g}{3}}\,Y_{max}^{\;3/2}\int_0^L\left(1-\frac{x}{L_T}\right)^{3/2}dx$$

The integral gives

$$Q_{CI}(L) = \frac{4}{15}\sqrt{\frac{2g}{3}}\,Y_{max}^{\;3/2}\,L_T\left[1-\left(1-\frac{L}{L_T}\right)^{5/2}\right]$$

If $L = L_T$, then all of the approach discharge Q_A is captured by the curb inlet

$$Q_A = Q_{CI}(L_T) = \frac{4}{15}\sqrt{\frac{2\,g}{3}}\,Y_{max}^{\;3/2}\,L_T$$

1.31

Inlet Efficiency, E

The curb inlet efficiency, E, is the ratio of the curb discharge that is captured by an inlet of length L, to the total approach discharge:

$$E = \frac{Q_{CI}(L)}{Q_A} = 1 - \left(1 - \frac{L}{L_T}\right)^{5/2}$$

FHWA studies (HEC-12) suggest that this theoretical relationship should be modified as

$$\boxed{E = 1 - \left(1 - \frac{L}{L_T}\right)^{1.8}}$$

FHWA

The bypass discharge, Q_B, is calculated from

$$Q_B = Q_A - Q_{CI} = Q_T\,(1 - E)$$

1.32

Inlet Capture Length

The length of curb inlet required to capture all of the approach gutter discharge is calculated from

$$L_T = \frac{15}{4}\sqrt{\frac{3}{2g}}\,\frac{Q_A}{Y_{max}^{3/2}}$$

Combine this with Izzard's equation for Y_{max}:

$$Y_{max} = \left[\frac{8}{3}\frac{n S_x Q_A}{\phi\sqrt{S_o}}\right]^{3/8}$$

$$L_T = \frac{15}{4}\sqrt{\frac{3}{2g}}\left(\frac{3\phi}{8}\right)^{9/16}\left(\frac{1}{nS_x}\right)^{9/16}(S_o)^{9/32}\,Q_A^{7/16}$$

In U.S. Customary units, this is often written as

$$\boxed{L_T = 0.60\left(\frac{1}{nS_x}\right)^{0.6}(S_o)^{0.3}(Q_A)^{0.42}}$$

FHwA

L_T - (ft); Q_A - (ft^3/s)

1.33

Example #2

A gutter (n = 0.014) carries a discharge of 5 cfs down a street with longitudinal slope of 2% and cross-slope 1:33 (S_x = 0.03). What fraction of the gutter discharge will be captured by a curb inlet that is 10 ft long?

Approach: 1) find Y_{max}; 2) find L_T; 3) find E; 4) and find Q_{CI} = E Q_A

1) With Izzard's equation for gutter flow we have

$$Y_{max} = \left[\frac{8 n S_x Q}{3\phi\sqrt{S_o}}\right]^{3/8} = \left[\frac{8\times 0.014\times 0.03\times 5}{3\times 1.5\times\sqrt{0.02}}\right]^{3/8} = 0.26\ ft$$

T = Y_{max} / S_x
= 0.26/0.03
= 8.5 ft

2) The inlet capture length is calculated using

$$L_T = 0.6\left(\frac{1}{0.014\times 0.03}\right)^{0.6}(0.02)^{0.3}(5)^{0.42} = 38.5\ ft$$

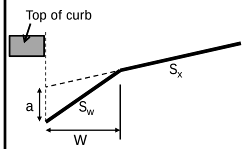
3) The capture efficiency is calculated from

$$E = 1 - (1 - L/L_T)^{1.8} = 1 - (1 - 10/38.5)^{1.8} = 0.42$$

4) The captured curb inlet discharge is Q_{CI} = 0.42 x 5 = <u>2.1 cfs</u>

1.34

Depressed Curb Inlet



$S_w = S_x + a/W$

E_o = fraction of total Q in the depressed gutter section

$$E_o = \left\{ 1 + \frac{(S_w/S_x)}{\left[1 + \frac{(S_w/S_x)}{(T/W)-1}\right]^{8/3} - 1} \right\}^{-1}$$

Equivalent cross slope, $S_e = S_x + (a/W)\ E_o$

Total Interception Length: $\boxed{L_T = 0.60\left(\frac{1}{nS_e}\right)^{0.6} (S_o)^{0.3} (Q_A)^{0.42}}$

Continue with inlet capture calculations using new L_T value.

1.35

Example #3

Repeat Example #2 for depressed inlet with 4-inch depressing (a = 0.33 ft) over depressing width 2 ft (W = 2 ft).

Approach: 1) find equivalent cross slope S_e; 2) find L_T; 3) find E; and 4) find $Q_{CI} = E\ Q_A$

1) $S_w = S_x + a/W = 0.195$ → $E_o = 0.74$ → $S_e = 0.03 + (0.33/2) * 0.74 = 0.15$

2) The inlet capture length is calculated using

$$L_T = 0.6\left(\frac{1}{0.014 \times 0.15}\right)^{0.6} (0.02)^{0.3} (5)^{0.42} = 14.7\ ft$$

3) The capture efficiency is calculated from

$$E = 1 - (1 - L/L_T)^{1.8} = 1 - (1 - 10/14.7)^{1.8} = 0.87$$

4) The captured curb inlet discharge is $Q_{CI} = 0.87 \times 5 =$ <u>4.4 cfs</u>

1.36

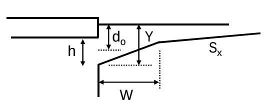
Curb Inlet in Sag

- water enters inlet from both sides
- h = height of curb inlet opening
- Y = depth at curb inlet opening
- d_o = depth to inlet centroid

- If Y < h → inlet acts as a weir with critical flow at inlet:
  $Q = (2/3)^{1.5}\ g^{0.5}\ Y^{1.5}\ L$

- If Y > 1.4 h → inlet acts as an orifice ($C_d \sim 2/3$)
  $Q = C_d\ (h\ L)\ (2\ g\ d_o)^{0.5}$

- For h < Y < 1.4 h → interpolate



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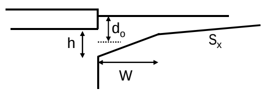
Example #4: Curb Inlet in Sag



Determine the length of a curb inlet in sag for a design discharge Q_{design} = 18 cfs. The following parameters hold.

T = 12 ft
S_x = 0.025
h = 6 inch
a = 4 inch
W = 2 ft

At the curb,

Y = T S_x + a = 12 (0.025) + (4/12)
= 0.633 ft = 7.6 inch

Y/h = 7.6/6 = 1.27 → neither criteria works! Need to try both.

1.38

Example (Cont.)

Weir-type flow:

$$Q/L = (2/3)^{3/2}\sqrt{g}\,Y^{3/2} = 3.09(7.6/12)^{1.5} = 1.56\ ft^2/s$$

Orifice-type flow:

d_o = Y – h/2 = 7.6 – 4/2 = 5.6 inch = 0.467 ft

$$Q/L = C_d\,h\sqrt{2g\,d_o} = (2/3)(6/12)\sqrt{2(32.2)\times 0.467} = 1.83\ ft^2/s$$

To be conservative, assume weir-type flow and

L = Q_{design} / (Q/L) = 18 / 1.56 = 11.5 ft (use 12 ft)

1.39

Topic 3: Estimating Peak Discharge

- Design of many stormwater hydraulic structures depend on the discharge they are required to control
- Examples include:
  - Inlets
  - Drains
  - Culverts
- Peak discharge is estimated using the Rational Method, limited by a minimum Time of Concentration (generally 6 to 10 minutes)

1.40

Rational Method – Calculation

Rational Method: $Q = C\ I\ A$

Q = Peak discharge (cfs)

C = Runoff coefficient (dimensionless)

I = Rainfall intensity (in/hr) from IDF curve

A = Drainage area (acres)

Units: 1 acre-inch/hr = 1.008 cfs

Useful conversions: 1 acre = 43,560 ft^2

1 sq. mile = 640 acres

1.41

Rational Method - Assumptions

The Rational Method is based on the following assumptions:

a) The peak discharge at any location is directly proportional to the average rainfall intensity during the time of concentration (for that location)

b) The time of concentration is the travel time from the most remote (in travel time, not necessarily distance) point in the contributing area to the location under consideration

c) The contributing area can be the entire drainage area upstream of the location or some subset of this area, such as only the directly connected impervious portion of the drainage area

1.42

Runoff Coefficient, C

- Fraction of the rainfall intensity (I) that contributes to the peak discharge (depends on rainfall intensity and duration)

- Typical values (ASCE):
  - Pavement 0.70 – 0.95
  - Urban business 0.70 – 0.95
  - Neighborhood 0.50 – 0.70
  - Residential
    - Single family 0.30 – 0.50
    - Suburban 0.25 – 0.40
  - Industrial
    - Light 0.50 – 0.80
    - Heavy 0.60 – 0.90

1.43

Rainfall Intensity: IDF Curves

- Variability in rainfall intensity with duration can be described by a model called the *Intensity-Duration-Frequency* (IDF) curve.
- Frequency refers to the return period of the event. The rainfall intensity with a 10 minute duration for an event with a 10 year return period will be greater than the corresponding intensity of an event with a 2 year return period.

1.44

IDF Curves

- Statistical (frequency) analysis of local rainfall records to identify how intensity (I) varies with rainfall duration (T_d) for different probability of occurrence or return period (T_R)
- IDF model equation:

$$I = \frac{a}{(T_d + b)^c}$$

1.45

TxDOT IDF Curves for Travis County

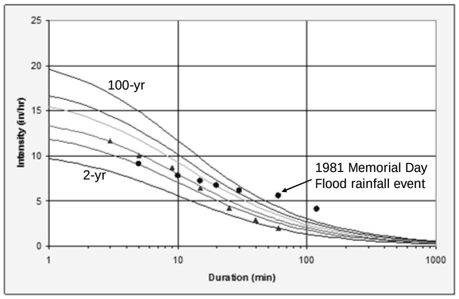
Return Period	2 year	5 year	10 year	25 year	50 year	100 year
a	56	69	77	87	91	103
b	8.1	8.6	8.6	8.6	8.6	8.1
c	0.796	0.780	0.775	0.766	0.751	0.752

$$I = \frac{a}{(T_d + b)^c}$$

- I (in/hr)
- T_d (min)

1.46

Travis County IDF Curves, including data from two rainfall events



Note: actual events do not follow IDF curves

1.47

Example #5

What is the rainfall intensity and depth for an event with 8 minute duration and 5 year return period?

From the IDF curve

$$I = \frac{69}{(8+8.6)^{0.780}} = 7.71 \text{ in/hr}$$

The corresponding depth is

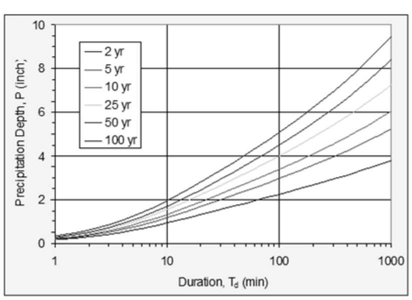
P = 7.71 x (8/60) = 1.03 inches

1.48

P-Td-TR Curves

Precipitation depth (P), duration (Td), return period (TR)

$$P = \frac{a(T_d/60)}{(T_d+b)^c}$$



1.49

Example #6 T_c Using Kinematic Wave

An inlet captures drainage from a 3 acre watershed (30% impervious). What is the peak discharge for a 5 year return period event?

Data. Pervious area: n = 0.4, L = 250 ft, S = 0.025, C = 0.25

Impervious (pavement): n = 0.014, L = 500 ft, S = 0.01, C = 0.95

Use of the kinematic wave equation to estimate the time of concentration requires the rainfall intensity, which in turn depends on the time of concentration. Approach is to choose a duration, calculate the rainfall intensity, then calculate the time of concentration, and finally compare with the assumed duration.

Assume T_d = 8 minutes (which gives I = 7.71 in/hr = 0.00018 ft/s; see Example #3). With the data above, the kinematic wave model gives (impervious) t_c = 315 sec = 5.3 min; and (pervious) t_c = 1180 sec = 19.7 min.

Repeat (see helpful hint on next page).

1.50

Example #6 (Cont.)

To find the time of concentration, we are combining the kinematic wave equation with the IDF curve equation. Taking into account unit conversions, these may be combined as follows:

$$\boxed{T_c = \frac{1}{60}\left(\frac{nL}{\phi\sqrt{S}}\right)^{0.6}\left(\frac{a/(12\times 3600)}{(T_d+b)^c}\right)^{-0.4}}$$

(Both T_c and T_d in minutes)

Trial and error give (impervious) T_c = 4.95 minutes and (pervious) T_c = 24.5 minutes. These durations correspond to rainfall intensities (impervious) I = 9.04 in/hr and (pervious) I = 4.50 in/hr.

We next need to determine whether the runoff from only the impervious area gives a greater peak discharge than runoff from the entire area.

1.51

Example #6 (Cont.)

Considering only the impervious area:

Q = 0.95 x 9.04 x 0.9 = 7.73 cfs

Considering the total drainage area, the rational method gives

Q = (0.95 x 0.9 + 0.25 x 2.1) x 4.50 = 6.21 cfs

The discharge from only the impervious area is larger and would be used to design the inlet and storm sewer for a peak discharge of 7.73 cfs.

1.52

Time of Concentration, T_c

- Description: T_c = drainage time from most hydraulically distant location within watershed to location of interest. Generally includes the following:

$$T_c = T_{overland\ flow} + T_{concentrated\ flow} + T_{channel\ flow}$$

- Kerby-Kirpick Method: Use Kerby equation for overland/concentrated flow and Kirpick equation for channel flow
  - Approximation for small to moderate size watersheds: use Kirpick equation to estimate T_c for channel flow and add 30 minutes to account for overland and shallow concentrated flow

1.53

Kerby (1959) Method (Overland Flow)

Area < 10 acre; slope < 0.01

$$\boxed{T_c(\min) = \left(\frac{2}{3}\frac{L\,N}{\sqrt{S}}\right)^{0.47}}$$

L = overland flow path length to defined channel (ft)

S = average watershed slope (ft/ft)

N = flow retardance factor:

N = 0.02	smooth impervious surface
N = 0.10	smooth, bare packed soil
N = 0.20	poor grass; moderately rough bare surface
N = 0.40	average grass
N = 0.60	deciduous forest
N = 0.80	dense grass; coniferous forest; deep ground liter

1.54

Kirpich (1940) – Channel Flow

$$\boxed{T_c(\min) = 0.0078\left(\frac{L}{\sqrt{S}}\right)^{0.77}}$$

- Multiply T_c by 0.4 if overland flow path is concrete or asphalt
- Multiply T_c by 0.2 if channel is concrete-lined

1.55

Topic 4 – Design of Storm Sewer Systems

- Inlet spacing
- Design criteria
- Watershed delineation
- Design procedure

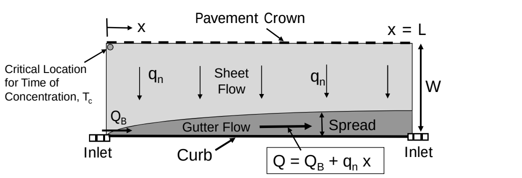
1.56

Inlet Spacing

- Inlet spacing is determined by limitations on spread of stormwater gutter flow across the roadway surface.
- Some inlet bypass (carry-over) of gutter flow is OK, except at roadway intersections where cross flow should be avoided.
- Read Section 8.VII (Street and Intersection Design; pg 250-260) from ASCE (1992) for classification of streets and limitations on pavement encroachment and cross flow.

1.57

Gutter Flow (Steady, Nonuniform)



$Q = Q_B + q_n x$

$q_n = C\ I\ W$

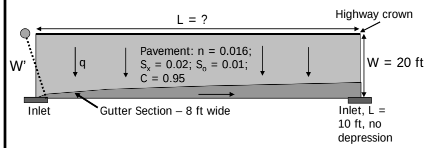
Maximum spread determines inlet spacing:

$$Q_A = \frac{3\phi\sqrt{S_o}}{8n} S_x^{5/3} T_{max}^{8/3} \quad \rightarrow \quad L = \frac{Q_A - Q_B}{q_n}$$

Izzard's Equation

1.58

Example #7 – Inlet Spacing



If the spread is limited to the gutter section (T_{max} = 8 ft), what is the maximum inlet spacing? Design frequency = 25 yrs; use minimum T_c = 6 min; and assume inlet bypass based on same conditions upstream.

Approach: 1) calculate Q_A based on maximum spread; 2) calculate inlet efficiency and bypass; 3) assume rainfall intensity based on limiting T_c and calculate inlet spacing; 4) check T_c based on L; 5) use new I and repeat 3) etc.

1) Using Izzard's eq., $Q_A = (3/8)\ [1.5\ (0.01)^{1/2}/0.016] \times (0.02)^{5/3} \times 8^{8/3} = 1.3$ cfs

2) The total inlet capture length is

$$L_T = 0.6\left(\frac{1}{0.016\times 0.02}\right)^{0.6}(0.01)^{0.3}(8.3)^{0.42} = 21\,ft$$

1.59

Example #7 (Cont.)

2) (Cont.) The inlet efficiency is $E = 1 - (1 - 10/21)^{1.8} = 0.69$. With this inlet efficiency, the bypass discharge is $Q_B = (1 - E)\ Q_A = 0.4$ cfs.

3) For a 25-yr event with $T_d = T_c$ (assumed T_c = 6 minutes for now), the rainfall intensity is $I = 87/(6 + 8.6)^{0.766} = 11.2$ in/hr = 0.000258 ft/s. The pavement drainage path length is approximately $W' = 20\ [1 + (0.01/0.02)^2]^{0.5}$ = 22.4 ft. The 'normal' lateral flow rate into the gutter section $q_n = 0.95 \times 0.000258 \times 20 = 0.0049$ ft^2/s. With this lateral flow rate, the inlet spacing is calculated from

$$L = \frac{1.3 - 0.4}{0.0049} = 180\,ft$$

1.60

Example #7 (Cont.)

4) The pavement drainage slope is $S = (S_x^2 + S_o^2)^{0.5} = 0.0224$. With I_o = C I = 0.95 x 11.2 = 10.6 in/hr = 0.000248 ft/s, the time of concentration for lateral flow from the pavement is calculated from

$$\Delta T_{c1} = \left(\frac{0.016\times 22.4}{1.5\times\sqrt{0.0224}}\right)^{0.6}\left(\frac{1}{0.000248}\right)^{0.4} = 37\,\text{sec}$$

For the flow through the gutter, $\alpha_g = 0.945\ (1.5)\ (0.02)^{0.33}\ (0.01)^{0.5}/0.016$ = 2.44 and q_n = 0.0050 ft^2/s. The time of concentration for gutter flow is

$$\Delta T_{c2} = \frac{4/3}{\alpha_g^{0.75}\,q_n}\left\{Q_A^{0.75} - Q_B^{0.75}\right\} = \frac{4/3}{(2.44)^{0.75}\times 0.0050}\left\{1.3^{0.75} - 0.4^{0.75}\right\} = 97\,\text{sec}$$

The total time of concentration is T_c = 37 + 97 = 134 sec = 2.2 min

5) This T_c value is less than T_d = 6 minutes, so there is no need to repeat the calculations. Use L = 180 feet.

1.61

Storm Sewer Design

- The basic approach for storm sewer design is similar to that used for design of inlet spacing for highway runoff.
- 1) A watershed area is delineated
- 2) time of concentration estimated
- 3) and the design rainfall is estimated using IDF curves and a duration equal to the time of concentration
- 4) Peak discharge is calculated using the rational method
- 5) Storm sewer pipe size is determined based on the peak discharge using Manning's equation, assuming that the sewer pipe flows full
- 6) Storm sewer network layout follows topography to the extent that is practical.

1.62

General Criteria: Storm Sewer Design

- Storm sewer size is determined by application of Manning's equation for the design peak discharge that the sewer pipe will carry; this discharge includes both inlet flow plus upstream sewer discharge
- Slope must be sufficient to maintain a velocity greater than 2-3 ft to prevent significant sedimentation in sewer pipe
- Manholes should be utilized at sewer junctions and at locations with significant changes in direction
- Slopes should be uniform between manholes; size increases generally occur at manhole (pipe size should never decrease in the downstream direction)
- There should be at least 3 ft of cover over the crown of the pipe to support earth and external loads

1.63

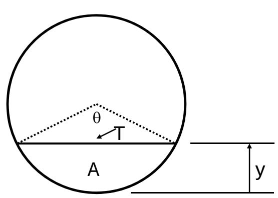
Circular Section, Diameter D

Central Angle, θ:

$$y = \frac{D}{2}\left(1 - \cos\left(\frac{\theta}{2}\right)\right)$$

$$A = \frac{D^2}{8}\left(\theta - \sin(\theta)\right)$$

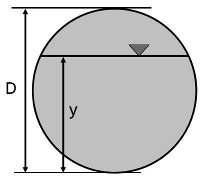
$$R_h = \frac{D}{4}\left(1 - \frac{\sin(\theta)}{\theta}\right)$$



$$T = D\sin\left(\frac{\theta}{2}\right)$$

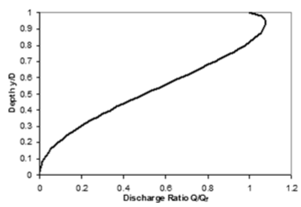
1.64

Circular Pipe (conduit)



Pipe-full discharge:

$$Q_f = \frac{\phi}{n}\left(\frac{\pi D^2}{4}\right)\left(\frac{D}{4}\right)^{2/3} S_o^{1/2}$$



- $Q > Q_f$ for $y > 0.8\,D$
- $Q = 1.076\,Q_f$ for $y/D = 0.938$

1.65

Size of Storm Sewer Pipe

Manning's equation for (circular) pipe:

$$\boxed{Q = \frac{\phi}{n}\left(\frac{\pi D^2}{4}\right)\left(\frac{D}{4}\right)^{2/3}\sqrt{S} \quad \rightarrow \quad D = \left(\frac{4^{5/3}\,nQ}{\pi\,\phi\sqrt{S}}\right)^{3/8}}$$

- This assumes that the pipe is flowing full under design conditions
- The discharge must include the peak flow from both upstream sewer pipe plus inlet flow

US Customary units

$$\boxed{D = 1.34\left(\frac{nQ}{\sqrt{S}}\right)^{3/8}}$$

1.66

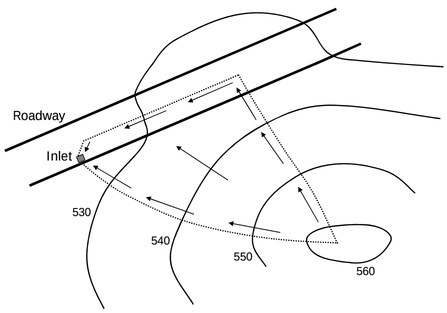
Watershed Delineation

- Watershed delineation includes estimation of contributing area size, slope, and land use classification. Drainage areas are delineated using topographic data, that is generally available from a number of sources.
- USGS "topo" maps may be accessed from a number of sources. A useful online source is

  http://www.topozone.com
- Modern practice uses "digital elevation model" (DEM) data and tools that help automate watershed delineation. An alternative is to manually delineate the watershed – this is the approach assumed herein.

1.67

Drainage Area Delineation



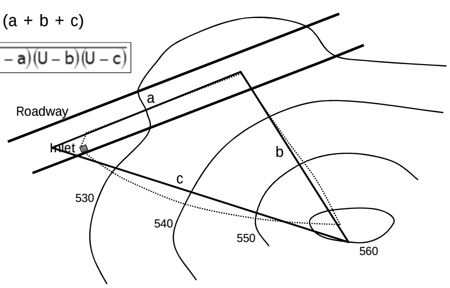
1.68

Area Estimation

Heron's formula

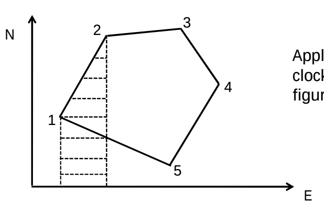
U = 0.5 (a + b + c)

$$\boxed{\text{Area} = \sqrt{U(U-a)(U-b)(U-c)}}$$



1.69

General Polygon



Apply trapezoidal rule clockwise around the figure

$$\boxed{\begin{aligned}Area &= 0.5(N_2+N_1)(E_2-E_1)+0.5(N_3+N_2)(E_3-E_2)+\ldots\\ &\ldots 0.5(N_5+N_4)(E_5-E_4)+0.5(N_1+N_5)(E_1-E_5)\end{aligned}}$$

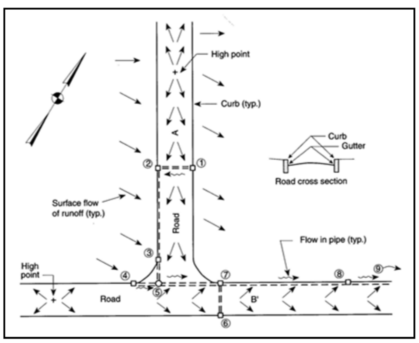
1.70

Storm Sewer Design Procedure

- Delineate the watershed contributing flow to each inlet. Calculate Σ(CA) for each inlet.
- Moving from upstream to downstream through the storm sewer drainage network, for each inlet calculate T_c including overland flow plus concentrated flow. Compare with T_c from upstream drainage areas including overland flow, concentrated flow, and channel (conduit) flow travel time. Select the largest T_c value for the inlet.
- Set $T_d = T_c$ and calculate the rainfall intensity using the IDF curve. Calculate the design discharge from $Q = \Sigma(CA)\ I$.
- Estimate the required conduit size based on the design discharge, using the next larger "commonly available" size.
- Adjust and verify all calculations considering selected conduit size, design discharge, and calculated travel times through conduits. Check for desired hydraulic grade line elevations for final design.

1.71

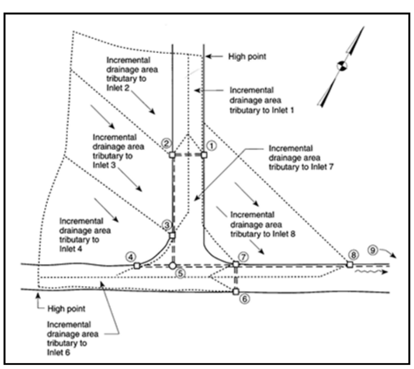
Example – Sewer Inlet and Pipe Layout



Example from Gribbin, 2002

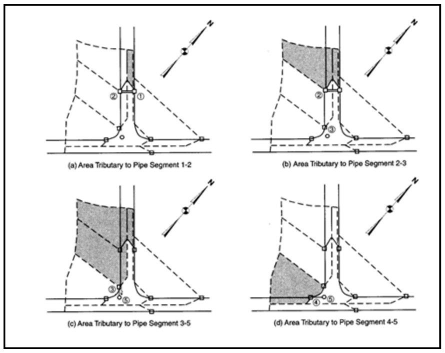
1.72

First Delineate Drainage Areas for Each Inlet



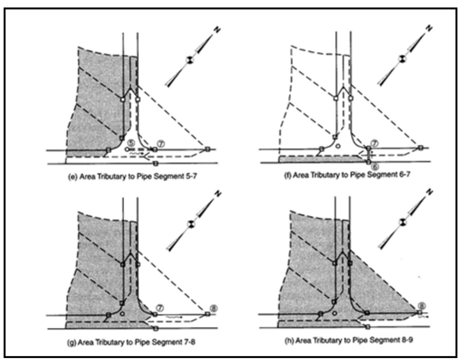
1.73

Inlet Drainage Areas - 1



1.74

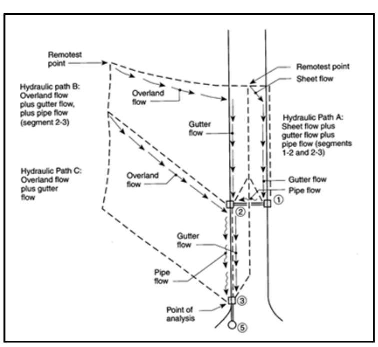
Inlet Drainage Areas - 2



1.75

Analysis of Travel Time to Pipe Segment

Three possible drainage paths leading to pipe segment 3-5. To find T_c, select the one with the longest travel time.



1.76

Suggested References

- Drainage of Highway Pavement, Hydraulic Engineering Circular No. 12, FHWA, March 1984.
- Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22, FHWA, November 1966 (2nd Ed., August 2001).
- Design and Construction of Urban Stormwater Management Systems, ASCE Manuals and Reports of Engineering Practice No. 77, ASCE, 1992.
- Stormwater Conveyance Modeling and Design, Haestad Methods, Haestad Press, 2003.
- Izzard, C.F., Hydraulics of Runoff from Developed Surfaces, Proc. 26th Annual Meeting, Highway Research Board, 1947.