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Design of Storm Water Management System

Part 1
Design of street gutters, inlets and storm sewer pipes

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Outline

- **Introduction**
- **Minor and Major Systems and their components**
- **Design Storm**
- **Design of storm sewer pipes**
- **Design of street gutters**
- **Design of street inlets**
- **Design of open channels**

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Introduction

- Stormwater management systems are designed to control the quantity, quality, timing and distribution of storm runoff.
- Other objectives include erosion control, reuse storage and groundwater recharge
- A typical urban stormwater management system has two distinct components; **minor system** and **major system**

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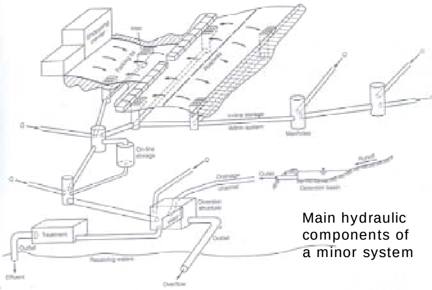

Main hydraulic components of a minor system

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Minor system

- Consists of gutters, inlets and storm sewers to route the runoff to receiving waters
- Typical design is based on return periods of 2 to 10 years

Land use (Minor drainage systems)	Design storm return period (years)
Residential	2-5
High-value general commercial area	2-10
Airports	2-10
High-value downtown business areas	5-10

Source: ASCE (1992)

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Major system

- Above-ground conveyance routes that transport stormwater from larger runoff events with return periods from 25 to 100 years
- In U.S. major urban conveyance systems are typically designed for a runoff with a 100-year return period

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Design of street gutters and inlets

- Pavements are designed with cross-slopes (1.5% to 6%)and longitudinal slopes (0.5% to 5%)
- Cross-slopes direct the incident rainfall to the sides of roadway (gutters) and longitudinal slopes direct the flow in the gutters to inlets
- The spacing between inlets is mainly controlled by rate of flow and allowable water spread toward the crown of the street.

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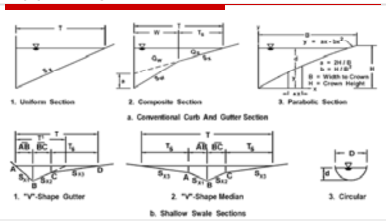
Typical gutter sections



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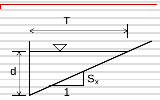
Modified Manning's formula for gutter flow

$$Q = 0.38\left(\frac{1}{nS_x}\right)d^{8/3}S_0^{1/2} \quad \text{(SI units)}$$

$$d = TS_x$$



$S_x =$ Street cross-slope

$d =$ Depth of flow at the curb

$T =$ Allowable width of spread (depends on type of street)

For proper drainage street cross-slope should be greater than 2% and longitudinal slope should be greater than 0.4%

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Typical Manning's n values for street gutters

Type of gutter or pavement	n
Concrete gutter	0.012
Asphalt pavement	
Smooth texture	0.013
Rough texture	0.016
Concrete gutter with asphalt pavement	
Smooth	0.013
Rough	0.015
Concrete pavement	
Float finish	0.014
Broom finish	0.016

Source: FHWA (1984)

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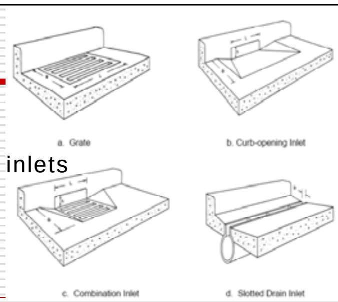
Curb inlets



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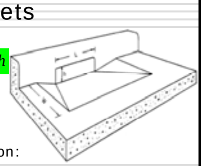
Design of curb inlets

$$Q_i = 1.27(L + 1.8W)d^{3/2} \quad d \le h$$

$L =$ Length of the curb opening

$W =$ Width of the inlet depression



For gutter without depression:

$$Q_i = 1.27Ld \quad d \le h$$

$$Q_i = 0.67Lh[2g(d - h/2)]^{1/2} \quad d \ge 1.4h$$

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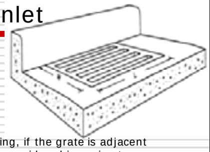
Design of grate inlet



Advantage: More capacity than a curb inlet

Disadvantage: May be clogged by debris

$$Q_i = 1.66 P d^{3/2} \quad d \leq 12\text{cm}$$

$P =$ Perimeter of the grate opening, if the grate is adjacent to curb then that side is not considered in perimeter

$$Q_i = 0.6 A \sqrt{2gd} \quad d > 43\text{cm}$$

$A =$ Total area of the opening

For 12cm<d<43cm: discharge lies between values calculated from above equations

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Design of grate inlet (Cont'd)

The minimum length, L, of clear opening parallel to the direction of flow is given as (ASCE, 1992):

$$L = 0.91 V (t + d)^{1/2}$$

$V =$ Average velocity of the water approaching the grate inlet (m/s)

$t =$ Thickness of the grate (m)

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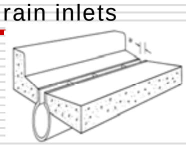
Design of slotted drain inlets



Slotted drains are used on curbed and uncurbed roadways. For slot widths greater than 4.45 cm, the length, L, of drain required to intercept a flow of Q_i is given as:

$$L = 0.817 Q_i^{0.42} S_0^{0.3} \left(\frac{1}{n S_x} \right)^{0.6}$$

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Design of storm sewer pipes

From Manning's formula

$$D = \left(\frac{3.21Qn}{\sqrt{S_0}}\right)^{3/8} \quad \text{(SI units)}$$

D = pipe diameter in m

Q = discharge (m^3/s)

S_0 = pipe slope

n = Manning's rougness factor

Manning's formula is valid only for fully rough flow, or $n^6\sqrt{DS_0/4} \geq 10^{-13}$

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Manning coefficient in closed conduits

Source: Chin (2000)

Material	n
Asbestos-cement pipe	0.011-0.015
Brick	0.013-0.017
Cast-iron pipe (cement lined and seal coated)	0.011-0.015
Concrete (monolithic)	
Smooth forms	0.012-0.014
Rough forms	0.015-0.017
Concrete pipes	0.011-0.015
Corrugated-metal pipe (1.3cmx6.4cm corrugations)	
Plain	0.022-0.026
Paved invert	0.018-0.022
Spun asphalt lined	0.011-0.015
Plastic pipe (smooth)	0.011-0.015
Vitrified clay pipes	0.011-0.015

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Design of storm sewer pipes

From Darcy-Weisbach equation

$$D = \left(\frac{0.811 fQ^2}{gS_0}\right)^{1/5}$$

g = acceleration due to gravity

f = friction factor

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{k_s/D}{3.7} + \frac{5.74}{R_N^{0.9}}\right) \quad \text{(Jain's approximation)}$$

k_s = pipe roughness

R_N = Reynolds number

Darcy-Weisbach equation is valid for both smooth and rough turbulent flows

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Storm sewer design specifications

- Storm sewer pipes are allowed to flow full and even under pressure. However, energy grade line should be at least 0.3m below the natural ground level.
- Pipe cover should be at least 0.9m
- Minimum allowable velocity: 0.6 to 0.9 m/s
- Maximum allowable velocity: 3.0 to 4.0 m/s
- Minimum pipe diameter: 300mm
- For pipe diameters greater than 600mm it is recommended to use reinforced or pre-stressed concrete.

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Losses

- Junction losses
- Manhole losses

$$h_m = k_c \frac{V^2}{2g}$$

$k_c =$ Head loss coefficient

=0.12 to 0.32 for single inflow and outflow pipes aligned opposite to each other

=1.0 to 1.8 for inflow and outflow pipes at right angles to each other.

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Example: Design of storm sewer

Given: Ground slope =0.5%, Discharge=0.43 m^3/s

Required: Concrete pipe diameter (n=0.013)

$$D = \left(\frac{3.21Qn}{\sqrt{S_0}}\right)^{3/8} = \left(\frac{3.21 \times 0.43 \times 0.013}{\sqrt{0.005}}\right)^{3/8} = 0.6\text{m}$$

$$n^6 \sqrt{DS_0 / 4} = (0.013)^6 \sqrt{0.6 \times 0.005 / 4} = 1.3 \times 10^{-13} \geq 10^{-13}$$

Which means Manning's formula is applicable

$$V = Q / A = 0.43 / \left(\pi \times 0.6^2 / 4\right) = 1.52\text{m/s}$$

Flow velocity is less than 4.0 m/s and greater than 0.6 m/s. So, the calculated diameter fulfils respective specifications

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Design of Storm Water Management System

Part 2
Design of open channels

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Applications of open channels

- Rivers, natural streams
- Storm drains
- Irrigation channels
- Sewer pipes and channels

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Basic Principles

Flow types

- Steady and unsteady (time)
- Uniform and non-uniform (space)
- Sub-critical and super-critical (Froude No.)

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Basic Principles

Manning's Equation

$$Q = \frac{C_n}{n} A R^{2/3} S_0^{1/2}$$

Q= Discharge
A= Area of cross-section
R= Hydraulic radius
S_0= Bed slope
C_n= 1.0 for SI units and 1.486 for British units

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Basic Principles

Solution of Manning's Equation

If depth of flow is unknown Manning's equation has to be solved by trials for most of the channel shapes.

- **Hit and trial method**
- **Newton's method**

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Newton's method

Q= actual value of discharge (constant)
Q_j= trial value of discharge

$$\text{Error} = f(y_j) = Q_j - Q$$

$$\left(\frac{df}{dy}\right)_j = \left(\frac{dQ_j}{dy_j}\right) = \frac{d}{dy_j}\left(\frac{C_n}{n} S_0^{1/2} A_j R_j^{2/3}\right)$$

$$= \frac{C_n}{n} S_0^{1/2} \left(\frac{2AR^{-1/3}}{3} \frac{dR}{dy} + R^{2/3} \frac{dA}{dy}\right)_j$$

$$= \frac{C_n}{n} A_j R_j^{2/3} S_0^{1/2} \left(\frac{2}{3R} \frac{dR}{dy} + \frac{1}{A} \frac{dA}{dy}\right)_j$$

$$= Q_j \left(\frac{2}{3R} \frac{dR}{dy} + \frac{1}{A} \frac{dA}{dy}\right)_j$$

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Newton's method

$$\left(\frac{df}{dy}\right)_j = \frac{0-f(y_j)}{y_{j+1}-y_j}$$

$$y_{j+1} = y_j - \frac{f(y_j)}{\left(\frac{df}{dy}\right)_j}$$

$$= y_j - \frac{1-Q/Q_j}{\left(\frac{2}{3R}\frac{dR}{dy}+\frac{1}{A}\frac{dA}{dy}\right)_j}$$

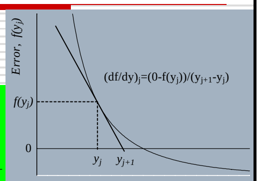

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TABLE 5.6.1
Geometric functions for channel elements

Section	Rectangle	Trapezoid	Triangle	Circle
Area A	$B_w y$	$(B_w + zy)y$	zy^2	$\frac{1}{8}(\theta - \sin\theta)d_0^2$
Wetted perimeter P	$B_w + 2y$	$B_w + 2y\sqrt{1+z^2}$	$2y\sqrt{1+z^2}$	$\frac{1}{2}\theta d_0$
Hydraulic radius R	$\frac{B_w y}{B_w + 2y}$	$\frac{(B_w+zy)y}{B_w + 2y\sqrt{1+z^2}}$	$\frac{zy}{2\sqrt{1+z^2}}$	$\frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)d_0$
Top width B	B_w	$B_w + 2zy$	$2zy$	$\left[\sin\left(\frac{\theta}{2}\right)\right]d_0$ or $2\sqrt{y(d_0 - y)}$
$\frac{2}{3R}\frac{dR}{dy} + \frac{1}{A}\frac{dA}{dy}$	$\frac{5B_w + 6y}{3y(B_w + 2y)}$	$\frac{(B_w+2zy)(5B_w+6y\sqrt{1+z^2})+4zy^2\sqrt{1+z^2}}{3y(B_w+zy)(B_w+2y\sqrt{1+z^2})}$	$\frac{8}{3y}$	$\frac{4(2\sin\theta + 3\theta - 5\theta\cos\theta)}{3d_0\theta(\theta - \sin\theta)\sin(\theta/2)}$ where $\theta = 2\cos^{-1}\left(1 - \frac{2y}{d_0}\right)$

Source: Chow, V. T., *Open-Channel Hydraulics*, McGraw-Hill, New York, 1959, Table 2.1, p. 21 (with additions).

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Best hydraulic section

The section that conveys the design discharge with minimum amount of lining material used in its construction.

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Best hydraulic section

To minimize the cost of material used in the channel, we need to minimize the wetted perimeter, for given roughness, discharge and bed slope. Consider a trapezoidal channel for example.

$$Q = \frac{C_n}{n} A R^{2/3} S_0^{1/2} \qquad \Rightarrow A = \left(\frac{Qn}{C_n S_0^{1/2}} \right)^{3/5} P^{2/5} \quad (1)$$

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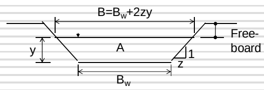
Best hydraulic section

From the geometry of trapezoidal section



$$A = B_w y + z y^2 \qquad P = B_w + 2y\sqrt{z^2+1}$$

Eliminating the base width

$$A = (P - 2y\sqrt{z^2+1}) y + z y^2 \quad (2)$$

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Best hydraulic section

From Eq. 1 and Eq. 2

$$(P - 2y\sqrt{z^2+1}) y + z y^2 = c P^{2/5} \qquad c = \left(\frac{Qn}{C_n S_0^{1/2}} \right)^{3/5}$$

Holding *z* constant and differentiating with respect to *y* and setting derivative equal to zero, we get

$$P = 4y\sqrt{z^2+1}) - 2zy$$

Similarly holding y constant and differentiating with respect to z and setting derivative equal to zero, we get

$$z = \frac{\sqrt{3}}{3} \approx 0.577$$

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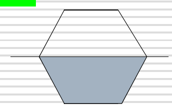
Best hydraulic section

Using this value of z we get the properties of the best trapezoidal section (most efficient section)

$$P = 2\sqrt{3}y \quad B_w = \frac{2}{\sqrt{3}}y \quad A = \sqrt{3}y^2$$

It may be shown from these properties that the best trapezoidal section is half hexagon and

$$P = 3B_w$$



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Geometric properties of best sections

Shape	Best Geometry	A	P	B
Trapezoidal	Half hexagon	$1.73y^2$	3.46y	2.31y
Rectangle	Half square	$2y^2$	4y	2y
Triangle	Half square	y^2	2.83y	2y
Semicircle	-	$0.5\pi y^2$	πy	2y
Parabola	-	$1.89y^2$	3.77y	2.83y

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Design specifications

- Minimum Permissible Velocity: 0.6 to 0.9 m/s
- Maximum Velocity: 3.5 m/s (Not strict)
- Longitudinal Slope should be preferably equal to the ground slope, but if the minimum permissible velocity is not achievable, the slope should be increased.
- Side slopes depend on the type of the material, i.e. angle of repose. USBR prefers a 1.5:1 (H:V) slope for usual sizes of lined channels.

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Recommended side slopes

Material	Side slope (H:V)
Rock	Nearly vertical
Muck and peat soils	¼:1
Stiff clay or concrete lining	½:1 to 1:1
Stone lining	1:1
Firm clay	1½:1
Loose, sandy earth	2:1
Sandy loam or porous clay	3:1

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Freeboard

Vertical distance between the water surface and top of the channel.

$F = 0.55\sqrt{Cy}$ $C = 0.01184Q + 1.493$

Minimum freeboard =30cm

Super-elevation

$$h_s = \frac{V^2 B}{g r_c}$$

V= average flow velocity
B= channel top width
r_c= radius of curvature

Recommended radius of curvature: $r_c \geq 3B$

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Design steps

1. Estimate the roughness coefficient, Manning's n for the lining material and freeboard coefficient, C for the design discharge.
2. Compute the normal depth of flow by Manning's equation, with assumed bed slope and if possible using best hydraulic cross-section.
3. Check the minimum velocity and Froude Number. Repeat step 2 and 3 if necessary to meet the specifications.
4. Calculate the required freeboard and increase the freeboard on the bends if required using the equation for super-elevation.

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Reinforcement

According to ASCE guidelines all channels carrying supercritical flow should be lined with concrete reinforced in both longitudinal and lateral directions.

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Example

- Design a lined trapezoidal channel to carry 20 m^3/s on a longitudinal slope of 0.0015. The lining of the channel is to be float-finished concrete (n=0.015). Consider:

(a) the best hydraulic section, and

(b) a section with side slopes of 1.5:1 (H:V).

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Solution

(a) For the best trapezoidal section

$$P = 2\sqrt{3}y \quad B_w = \frac{2}{\sqrt{3}}y \quad A = \sqrt{3}y^2 \qquad z = \frac{\sqrt{3}}{3} \approx 0.577$$

$$B_w = 1.15y \quad z = 0.58 \quad R = A/P = 0.5y$$

Using Manning's formula

$$20 = \frac{1}{0.015}\left(1.73y^2\right)\left(0.5y\right)^{2/3}\left(0.0015\right)^{1/2}$$

$$y^{8/3} = 7.12 \quad \Rightarrow \quad y = 2.09\text{m}$$

$$V = \frac{Q}{A} = \frac{20}{1.73 \times 2.09^2} = 2.6\,\text{m/s}$$ >0.6 m/s O.K.

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Solution (cont'd)

The hydraulic depth $D = \frac{A}{B} = \frac{1.73y^2}{2.31y} = 1.6\text{m}$

Froude number:

$$F_r = \frac{V}{\sqrt{gD}} = \frac{2.6}{\sqrt{9.81 \times 1.6}} = 0.66$$ <1, Sub-critical flow

The required freeboard

$$C = 0.01184Q + 1.493 = 0.01184 \times 20 + 1.493 = 1.7$$

$$F = 0.55\sqrt{C \times 2.09} = 0.55\sqrt{1.7 \times 2.09} = 1.04\text{m}$$

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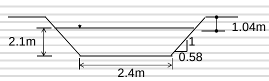
Solution (cont'd)

Designed best trapezoidal cross-section



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Solution (cont'd)

(b) If the channel side slopes are 1.5:1 then z=1.5

$$P = 4y\sqrt{1+z^2} - 2zy = 4.21y \qquad B_w = P - 2y\sqrt{1+z^2} = 0.6y$$

$$A = (B_w + zy)y = 2.1y^2 \qquad R = A/P = 0.499y$$

Using Manning's formula

$$20 = \frac{1}{0.015}(2.1y^2)(0.499y)^{2/3}(0.0015)^{1/2}$$

$$y^{8/3} = 5.86 \quad \Rightarrow \quad y = 1.94\text{m} \quad A = 2.1y^2 = 2.1 \times 1.94^2 = 7.9\text{m}^2$$

$$V = Q/A = 20/7.9 = 2.53\text{m/s}$$ >0.6m/s O.K.

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Solution (cont'd)

Hydraulic depth $D = \frac{A}{B} = \frac{2.1y^2}{3.6y} = 1.13\text{m}$

Froude number

$$F_r = \frac{V}{\sqrt{gD}} = \frac{2.53}{\sqrt{9.81 \times 1.13}} = 0.76$$ <1 Subcritical flow

The required freeboard

$C = 0.01184Q + 1.493 = 0.01184 \times 20 + 1.493 = 1.7$

$F = 0.55\sqrt{1.7 \times 1.94} = 1.0\text{m}$

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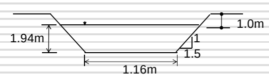
Solution (cont'd)

Designed trapezoidal cross-section with side slopes of 1.5



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References

ASCE (1992), Design and Construction of Urban Stromwater Management Systems, ASCE, New York

Chin, D. A. (2000), Water Resources Engineering, Prentice Hall Inc.

Chow, V. T. et. Al. (1985), Applied Hydrology, McGraw-Hill

FHWA(1984), HEC-12, U.S. Department of Transportation

FHWA(2001), Urban Drainage Design Manual, U.S. Department of Transportation

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