The use of depressed inlets and combination inlets enhances the interception capacity of the inlet. Example 4-7 determined the interception capacity of a depressed curved vane grate, 0.6 m by 0.6 m (2 ft by 2 ft), Example 4-9 for an undepressed curb opening inlet, length = 3.0 m (9.8 ft) and a depressed curb opening inlet, length = 3.0 m (9.8 ft), and Example 4-10 for a combination of 0.6 m by 0.6 m (2 ft by 2 ft) depressed curve vane grate located at the downstream end of 3.0 m (9.8 ft) long depressed curb opening inlet. The geometries of the inlets and the gutter slopes were consistent in the examples and Table 4-6 summarizes a comparison of the intercepted flow of the various configurations.

Table 4-6. Comparison of Inlet Interception Capacities.

Inlet Type	Intercepted Flow, Q_i
Curved Vane - Depressed	0.033 m^3/s (1.2 ft^3/s) (Example 4-7)
Curb Opening - Undepressed	0.031 m^3/s (1.1 ft^3/s) (Example 4-9 (1))
Curb Opening - Depressed	0.045 m^3/s (1.59 ft^3/s) (Example 4-9 (2))
Combination - Depressed	0.049 m^3/s (1.76 ft^3/s) (Example 4-10)

From Table 4-6, it can be seen that the combination inlet intercepted approximately 100% of the total flow whereas the curved vane grate alone only intercepted 66% of the total flow. The depressed curb opening intercepted 90% of the total flow. However, if the curb opening was undepressed, it would have only intercepted 62% of the total flow.

4.4.5. Interception Capacity of Inlets In Sag Locations

Inlets in sag locations operate as weirs under low head conditions and as orifices at greater depths. Orifice flow begins at depths dependent on the grate size, the curb opening height, or the slot width of the inlet. At depths between those at which weir flow definitely prevails and those at which orifice flow prevails, flow is in a transition stage. At these depths, control is ill-defined and flow may fluctuate between weir and orifice control. Design procedures presented here are based on a conservative approach to estimating the capacity of inlets in sump locations.

The efficiency of inlets in passing debris is critical in sag locations because all runoff which enters the sag must be passed through the inlet. Total or partial clogging of inlets in these locations can result in hazardous ponded conditions. Grate inlets alone are not recommended for use in sag locations because of the tendencies of grates to become clogged. Combination inlets or curb-opening inlets are recommended for use in these locations.

4.4.5.1. Grate Inlets in Sags

A grate inlet in a sag location operates as a weir to depths dependent on the size of the grate and as an orifice at greater depths. Grates of larger dimension will operate as weirs to greater depths than smaller grates.

$Q_i = C_w P d^{1.5}$ (4-26)

where:

P = Perimeter of the grate in m (ft) disregarding the side against the curb
C_w = 1.66 (3.0 in English units)
d = Average depth across the grate; 0.5 ($d_1 + d_2$), m (ft)

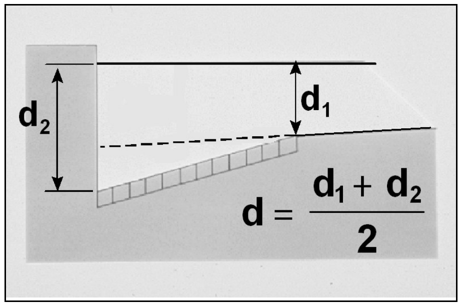

Figure 4-17. Definition of depth.

The capacity of a grate inlet operating as an orifice is:

$Q_i = C_o A_g (2 g d)^{0.5}$ (4-27)

where:

C_o = Orifice coefficient = 0.67
A_q = Clear opening area of the grate, m^2 (ft^2)
g = 9.81 m/s^2 (32.16 ft/s^2)

Use of Equation 4-27 requires the clear area of opening of the grate. Tests of three grates for the Federal Highway Administration(27) showed that for flat bar grates, such as the P-50x100 and P-30 grates, the clear opening is equal to the total area of the grate less the area occupied by longitudinal and lateral bars. The curved vane grate performed about 10% better than a grate with a net opening equal to the total area less the area of the bars projected on a horizontal plane. That is, the projected area of the bars in a curved vane grate is 68% of the total area of the grate leaving a net opening of 32%, however the grate performed as a grate with a net opening of 35%. Tilt-bar grates were not tested, but exploration of the above results would indicate a net opening area of 34% for the 30-degree tilt-bar and zero for the 45-degree tilt-bar grate. Obviously, the 45-degree tilt-bar grate would have greater than zero capacity. Tilt-bar and curved vane grates are not recommended for sump locations where there is a chance that operation would be as an orifice. Opening ratios for the grates are given on Chart 9.

Chart 9 is a plot of Equations 4-26 and 4-27 for various grate sizes. The effects of grate size on the depth at which a grate operates as an orifice is apparent from the chart. Transition from weir to orifice flow results in interception capacity less than that computed by either the weir or the orifice equation. This capacity can be approximated by drawing in a curve between the lines representing the perimeter and net area of the grate to be used.

Example 4-11 illustrates use of Equations 4-26 and 4-27 and Chart 9.

Example 4-11

Given: *Under design storm conditions a flow to the sag inlet is 0.19 m^3/s (6.71 ft^3/s). Also,*

S_x = S_W = 0.05 m/m (ft/ft)
n = 0.016
$T_{allowable}$ = 3 m (9.84 ft)

Find: *Find the grate size required and depth at curb for the sag inlet assuming 50% clogging where the width of the grate, W, is 0.6 m (2.0 ft).*

Solution:

SI Units

Step 1. Determine the required grate perimeter.

Depth at curb, d_2

$d_2 = T\,S_x = (3.0)\,(0.05)$
$d_2 = 0.15$ m

Average depth over grate

$d = d_2 - (W/2)\,S_W$
$d = 0.15 - (0.6/2)(.05)$
$d = 0.135$ m

From Equation 4-26 or Chart 9

$P = Q_i / [C_w\, d^{1.5}]$
$P = (0.19)/[(1.66)(0.135)^{1.5}]$
$P = 2.31$ m

English Units

Step 1. Determine the required grate perimeter.

Depth at curb, d_2

$d_2 = T\,S_x = (9.84)\,(0.05)$
$d_2 = 0.49$ ft

Average depth over grate

$d = d_2 - (W/2)\,S_W$
$d = 0.49 - (2.0/2)(.05)$
$d = 0.44$ ft

From Equation 4-26 or Chart 9

$P = Q_i / [C_w\, d^{1.5}]$
$P = (6.71)/[(3.0)(0.44)^{1.5}]$
$P = 7.66$ ft

Some assumptions must be made regarding the nature of the clogging in order to compute the capacity of a partially clogged grate. If the area of a grate is 50% covered by debris so that the debris-covered portion does not contribute to interception, the effective perimeter will be reduced by a lesser amount than 50%. For example, if a 0.6 m by 1.2 m (2 ft by 4 ft) grate is clogged so that the effective width is 0.3 m (1 ft), then the perimeter, P = 0.3 + 1.2 + 0.3 = 1.8 m (6 ft), rather than 2.31 m (7.66 ft), the total perimeter, or 1.2 m (4 ft), half of the total perimeter. The area of the opening would be reduced by 50% and the perimeter by 25%. Therefore, assuming 50% clogging along the length of the grate, a 1.2 m by 1.2 m (4 ft by 4 ft), 0.6 m by 1.8 m (2 ft by 6 ft), or a .9 m by 1.5 m (3 ft by 5 ft) grate would meet requirements of a 2.31 m (7.66 ft) perimeter 50% clogged.

Assuming 50% clogging along the grate length,

SI Units:

$P_{effective}$ = 2.4 m = (0.5) (2) W + L

if W = 0.6 m *then* L ≥ 1.8 m
if W = 0.9 m *then* L ≥ 1.5 m

English Units:

$P_{effective}$ = 8.0 = (0.5) (2) W + L

if W = 2 ft *then* L ≥ 6 ft
if W = 3 ft *then* L ≥ 5 ft

SI Units (continued)

Select a double 0.6 m by 0.9 m grate.

$P_{effective}$ = (0.5) (2) (0.6) + (1.8)
$P_{effective}$ = 2.4 m

Step 2. Check depth of flow at curb using Equation 4-26 or Chart 9.

$d = [Q/(C_w P)]^{0.67}$
$d = [0.19/((1.66)(2.4))]^{0.67}$
$d = 0.130$ m

Therefore, ok

English Units (continued)

Select a double 2 ft by 3 ft grate.

$P_{effective}$ = (0.5) (2) (2.0) + (6)
$P_{effective}$ = 8 ft

Step 2. Check depth of flow at curb using Equation 4-26 or Chart 9.

$d = [Q/(C_w P)]^{0.67}$
$d = [6.71/((3.0 (8.0)]^{0.67}$
$d = 0.43$ ft

Therefore, ok

Conclusion:

A double 0.6 m by 0.9 m (2 ft by 3 ft) grate 50% clogged is adequate to intercept the design storm flow at a spread which does not exceed design spread. However, the tendency of grate inlets to clog completely warrants consideration of a combination inlet or curb-opening inlet in a sag where ponding can occur, and flanking inlets in long flat vertical curves.

4.4.5.2. Curb-Opening Inlets

The capacity of a curb-opening inlet in a sag depends on water depth at the curb, the curb opening length, and the height of the curb opening. The inlet operates as a weir to depths equal to the curb opening height and as an orifice at depths greater than 1.4 times the opening height. At depths between 1.0 and 1.4 times the opening height, flow is in a transition stage.

Spread on the pavement is the usual criterion for judging the adequacy of a pavement drainage inlet design. It is also convenient and practical in the laboratory to measure depth at the curb upstream of the inlet at the point of maximum spread on the pavement. Therefore, depth at the curb measurements from experiments coincide with the depth at curb of interest to designers. The weir coefficient for a curb-opening inlet is less than the usual weir coefficient for several reasons, the most obvious of which is that depth measurements from experimental tests were not taken at the weir, and drawdown occurs between the point where measurement were made and the weir.

The weir location for a depressed curb-opening inlet is at the edge of the gutter, and the effective weir length is dependent on the width of the depressed gutter and the length of the curb opening. The weir location for a curb-opening inlet that is not depressed is at the lip of the curb opening, and its length is equal to that of the inlet, as shown in Chart 10.

The equation for the interception capacity of a depressed curb-opening inlet operating as a weir is:

$$Q_i = C_w (L + 1.8 W) d^{1.5} \quad (4\text{-}28)$$

where:

C_w = 1.25 (2.3 in English Units)
L = Length of curb opening, m (ft)
W = Lateral width of depression, m (ft)
d = Depth at curb measured from the normal cross slope, m (ft), i.e., $d = T\ S_x$

The weir equation is applicable to depths at the curb approximately equal to the height of the opening plus the depth of the depression. Thus, the limitation on the use of Equation 4-28 for a depressed curb-opening inlet is:

$$d \leq h + a/(1000) \quad (d \leq h + a / 12, \text{ in English units}) \qquad (4\text{-}29)$$

where:

h = Height of curb-opening inlet, m (ft)
a = Depth of depression, mm (in)

Experiments have not been conducted for curb-opening inlets with a continuously depressed gutter, but it is reasonable to expect that the effective weir length would be as great as that for an inlet in a local depression. Use of Equation 4-28 will yield conservative estimates of the interception capacity.

The weir equation for curb-opening inlets without depression becomes:

$$Q_i = C_w\ L\ d^{1.5} \qquad (4\text{-}30)$$

Without depression of the gutter section, the weir coefficient, C_w, becomes 1.60 (3.0, English system). The depth limitation for operation as a weir becomes $d \leq h$.

At curb-opening lengths greater than 3.6m (12 ft), Equation 4-30 for non-depressed inlet produces intercepted flows which exceed the values for depressed inlets computed using Equation 4-28. Since depressed inlets will perform at least as well as non-depressed inlets of the same length, Equation 4-30 should be used for all curb opening inlets having lengths greater than 3.6 m (12 ft).

Curb-opening inlets operate as orifices at depths greater than approximately 1.4 times the opening height. The interception capacity can be computed by Equation 4-31a and Equation 4-31b. These equations are applicable to depressed and undepressed curb-opening inlets. The depth at the inlet includes any gutter depression.

$$Q_i = C_o\ h\ L(2\ g\ d_o)^{0.5} \qquad (4\text{-}31a)$$

or

$$Q_i = C_o\ A_g\ \{2g\ [d_i - (h/2)]\}^{0.5} \qquad (4\text{-}31b)$$

where:

C_o = Orifice coefficient (0.67)
d_o = Effective head on the center of the orifice throat, m (ft)
L = Length of orifice opening, m (ft)
A_g = Clear area of opening, m^2 (ft^2)
d_i = Depth at lip of curb opening, m (ft)

h = Height of curb-opening orifice, m (ft)

The height of the orifice in Equations 4-31a and 4-31b assumes a vertical orifice opening. As illustrated in Figure 4-18, other orifice throat locations can change the effective depth on the orifice and the dimension (d_i - h/2). A limited throat width could reduce the capacity of the curb-opening inlet by causing the inlet to go into orifice flow at depths less than the height of the opening.

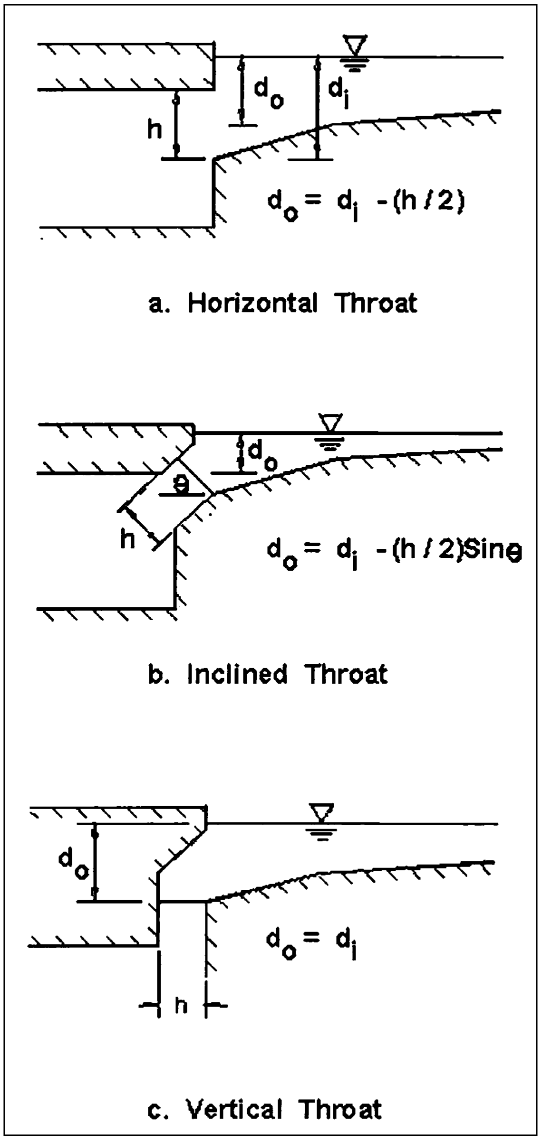

Figure 4.18. Curb-opening inlets.

For curb-opening inlets with other than vertical faces (see Figure 4-18), Equation 4-31a can be used with:

h = orifice throat width, m (ft)
d_o = effective head on the center of the orifice throat, m (ft)

Chart 10 provides solutions for Equations 4-28 and 4-31 for depressed curb-opening inlets, and Chart 11 provides solutions for Equations 4-30 and 4-31 for curb-opening inlets without depression. Chart 12 is provided for use for curb openings with other than vertical orifice openings.

Example 4-12 illustrates the use of Charts 11 and 12.

Example 4-12

Given: *Curb opening inlet in a sump location with*

L = 2.5 m (8.2 ft)
h = 0.13 m (0.43 ft)

(1) Undepressed curb opening

S_x = *0.02*
T = 2.5 m (8.2 ft)

(2) Depressed curb opening

S_x = *0.02*
a = 25 mm (1 in) local
W = 0.6 m (2 ft)
T = 2.5 m (8.2 ft)

Find: Q_i

Solution (1): *Undepressed*

<u>SI Units</u>

Step 1. Determine depth at curb.

$d = T S_x = (2.5)(0.02)$
$d = 0.05$ m
$d = 0.05 \text{ m} \leq h = 0.13 \text{ m}$,
therefore weir flow controls

Step 2. Use Equation 4-30 or Chart 11 to find Q_i.

$Q_i = C_w L d^{1.5}$
$Q_i = (1.60)(2.5)(0.05)^{1.5}$
$= 0.045 \text{ m}^3/\text{s}$

<u>English Units</u>

Step 1. Determine depth at curb.

$d = T S_x = (8.2)(0.02)$
$d = 0.16$ ft
$d = 0.16 \text{ ft} \leq h = 0.43 \text{ ft}$,
therefore weir flow controls

Step 2. Use Equation 4-30 or Chart 11 to find Q_i.

$Q_i = C_w L d^{1.5}$
$Q_i = (3.0)(8.2)(0.16)^{1.5}$
$= 1.6 \text{ ft}^3/\text{s}$

Solution (2): Depressed

SI Units

Step 1. Determine depth at curb, d_i

d_i = $d + a$
d_i = $S_x T + a$
d_i = $(0.02)(2.5) + 25/1000$
d_i = 0.075 m
d_i = 0.075 m < $h = 0.13$ m, therefore weir flow controls

Step 2. Use Equation 4-28 or Chart 10 to find Q_i.

P = $L + 1.8 W$
P = 2.5 m + $(1.8)(0.6)$
P = 3.58 m

Q_i = $C_w (L + 1.8 W) d^{1.5}$
Q_i = $(1.25)(3.58)(0.05)^{1.5}$
Q_i = 0.048 m^3/s

English Units

Step 1. Determine depth at curb, d_i

d_i = $d + a$
d_i = $S_x T + a$
d_i = $(0.02)(8.2) + 1/12$
d_i = 0.25 ft
d_i = 0.25 ft < $h = 0.43$ ft, therefore weir flow controls

Step 2. Use Equation 4-28 or Chart 10 to find Q_i.

P = $L + 1.8 W$
P = $8.2 + (1.8)(2.0)$
P = 11.8 ft

Q_i = $C_w (L + 1.8 W) d^{1.5}$
Q_i = $(2.3)(11.8)(0.16)^{1.5}$
Q_i = 1.7 ft^3/s

The depressed curb-opening inlet has 10% more capacity than an inlet without depression.

4.4.5.3 Slotted Inlets

Slotted inlets in sag locations perform as weirs to depths of about 0.06 m (0.2 ft), dependent on slot width. At depths greater than about 0.12 m, (0.4 ft), they perform as orifices. Between these depths, flow is in a transition stage. The interception capacity of a slotted inlet operating as a weir can be computed by an equation of the form:

$$Q_i = C_w L d^{1.5} \quad (4\text{-}32)$$

where:

- C_w = Weir coefficient; various with flow depth and slot length; typical value is approximately 1.4 (2.48 for English units)
- L = Length of slot, m (ft)
- d = Depth at curb measured from the normal cross slope, m (ft)

The interception capacity of a slotted inlet operating as an orifice can be computed by Equation 4-33:

$$Q_i = 0.8 L W (2 g d)^{0.5} \quad (4\text{-}33)$$

where:

W	=	Width of slot, m (ft)
L	=	Length of slot, m (ft)
d	=	Depth of water at slot for d > 0.12 m (0.4 ft), m (ft)
g	=	9.81 m/s^2 (32.16 ft/s^2 in English units)

For a slot width of 45 mm (1.75 in), Equation 4-33 becomes:

$$Q_i = C_D\ L\ d^{0.5} \tag{4-34}$$

where:

C_D = 0.16 (0.94 for English units)

Chart 13 provides solutions for weir and orifice flow conditions as represented by Equations 4-32 and 4-33. As indicated in Chart 13, the transition between weir and orifice flow occurs at different depths. To conservatively compute the interception capacity of slotted inlets in sump conditions in the transition area, orifice conditions should be assumed. Due to clogging characteristics, slotted drains are not recommended in sag locations.

Example 4-13

Given: *A slotted inlet located along a curb having a slot width of 45 mm (1.75 in). The gutter flow at the upstream end of the inlet is 0.14 m^3/s (4.9 ft^3/s).*

Find: *The length of slotted inlet required to limit maximum depth at the curb to 0.09 m (3.6 in) assuming no clogging.*

Solution:

SI Units	***English Units***
From Chart 13A with Q = 0.14 m^3/s and d = 0.09, L = 3.66 m say 4.0 m	*From Chart 13B with Q = 4.9 ft^3/s and d = 3.6 in, L = 10 ft*

Note: Since the point defined by Q and d on Chart 13 falls in the weir flow range, Equation 4-32 defines the flow condition. However, Equation 4-32 cannot be directly applied since C_w varies with both flow depth and slot length.

4.4.5.4 Combination Inlets

Combination inlets consisting of a grate and a curb opening are considered advisable for use in sags where hazardous ponding can occur. Equal length inlets refer to a grate inlet placed along side a curb opening inlet, both of which have the same length. A sweeper inlet refers to a grate inlet placed at the downstream end of a curb opening inlet. The curb opening inlet is longer than the grate inlet and intercepts the flow before the flow reaches the grate. The sweeper inlet is more efficient than the equal length combination inlet and the curb opening has the ability to intercept any debris which may clog the grate inlet. The interception capacity of the equal length combination inlet is essentially equal to that of a grate alone in weir flow. In orifice flow, the capacity of the equal length combination inlet is equal to the capacity of the grate plus the capacity of the curb opening.

Equation 4-26 and Chart 9 can be used for grates in weir flow or combination inlets in sag locations. Assuming complete clogging of the grate, Equations 4-28, 4-30, and 4-31 and Charts 10, 11 and 12 for curb-opening inlets are applicable.

Where depth at the curb is such that orifice flow occurs, the interception capacity of the inlet is computed by adding Equations 4-27 and 4-31a as follows:

$$Q_i = 0.67\ A_g\ (2\ g\ d)^{0.5} + 0.67\ h\ L\ (2\ g\ d_o)^{0.5} \qquad (4\text{-}35)$$

where:

A_g	=	Clear area of the grate, m^2 (ft^2)
g	=	9.81 m/s^2 (32.16 ft/s^2 in English units)
d	=	Average depth over the grate, m (ft)
h	=	Height of curb opening orifice, m (ft)
L	=	Length of curb opening, m (ft)
d_o	=	Effective depth at the center of the curb opening orifice, m (ft)

Trial and error solutions are necessary for determining the depth at the curb for a given flow rate using Charts 9, 10, and 11 for orifice flow. Different assumptions for clogging of the grate can also be examined using these charts as illustrated by the following example.

Example 4-14

Given: *A combination inlet in a sag location with the following characteristics:*

Grate - 0.6 m by 1.2 m (2 ft by 4 ft) P-50

Curb opening –

L	=	*1.2 m (4 ft)*
h	=	*0.1 m (3.9 in)*
Q	=	*0.15 m^3/s (5.3 ft^3/s)*
S_x	=	*0.03 m/m (ft/ft)*

Find: *Depth at curb and spread for:*

(1) Grate clear of clogging
(2) Grate 100% clogged

Solution (1):

SI Units

Step 1. Compute depth at curb.

Assuming grate controls interception:

$P = 2W + L = 2(0.6) + 1.2$
$P = 2.4\ m$

From Equation 4-26 or Chart 9

$d_{avg} = [Q_i / (C_w P)]^{0.67}$
$d_{avg} = [(0.15) / \{(1.66)(2.4)\}]^{0.67}$
$= 0.11\ m$

Step 2. Compute associated spread.

$d = d_{avg} + S_x W/2$
$d = 0.11 + .03\ (0.6)/2 = 0.119\ m$
$T = d / S_x = (0.119) / (0.03)$
$T = 3.97\ m$

English Units

Step 1. Compute depth at curb.

Assuming grate controls interception:

$P = 2W + L = 2(2) + 4$
$P = 8.0\ ft$

From Equation 4-26 or Chart 9

$d_{avg} = [Q_i / (C_w P)]^{0.67}$
$d_{avg} = [(5.3) / \{(3.0)(8.0\}]^{0.67}$
$= 0.36\ ft$

Step 2. Compute associated spread.

$d = d_{avg} + S_x W/2$
$d = 0.36 + .03(2)/2 = 0.39$
$T = d / S_x = (0.39 / (0.03)$
$T = 13\ ft$

Solution (2):

SI Units

Step 1. Compute depth at curb.

Assuming grate clogged. Using Chart 11 or Equation 4-31b with

$Q = 0.15\ m^3/s$

$d = \{Q_i/(C_o\ h\ L)\}^2 / (2g) + h/2$
$d = \{(0.15)/[(0.67)(0.10)(1.2)]\}^2/[(2)(9.81)]+(0.1/2)$
$d = 0.24\ m$

Step 2. Compute associated spread.

$T = d / S_x$
$T = (0.24) / (0.03)$
$T = 8.0\ m$

English Units

Step 1. Compute depth at curb.

Assuming grate clogged. Using Chart 11 or Equation 4-31b with

$Q = 5.3\ ft^3/s$

$d = \{Q_i/(C_o\ h\ L)\}^2 / (2g) + h/2$
$d = \{(5.3)/[(0.67)(0.325)(4)]\}^2/[(2)(32.2)]+(0.325/2)$
$d = 0.74\ ft$

Step 2. Compute associated spread.

$T = d / S_x$
$T = (0.74) / (0.03)$
$T = 24.7\ ft$

Interception by the curb-opening only will be in a transition stage between weir and orifice flow with a depth at the curb of about 0.24 m (0.8 ft). Depth at the curb and spread on the pavement would be almost twice as great if the grate should become completely clogged.