Chapter 5 - Roadway Pavement Drainage

The paved surface of the driving lanes is the critical area of interaction between vehicles and the roadway; effective drainage of the pavement facilitates safe roadway use. Water on the pavement adversely affects safe use of the road, interrupts traffic, reduces skid resistance, increases potential for hydroplaning, and limits visibility by splash and spray from traffic (AASHTO 2014).

Pavement drainage design involves knowledge and consideration of surface drainage, gutter flow, and inlet capacity. The design of these elements depends on the design rainfall frequency and the allowable spread of stormwater on the pavement surface. This chapter presents information for the design of roadway features to meet the desired safety and serviceability levels. The chapter draws on HEC-12, Drainage of Highway Pavements (FHWA 1984), and AASHTO's Drainage Manual (2014) for most of the information presented.

5.1 Spread

The width of pavement (outward from the face of curb) covered by water during rainfall is called "spread." Spread at any point on the roadway relates to the intensity and duration of rainfall. Allowable spread represents the maximum width of pavement covered during the design storm. Designers also evaluate spread associated with a larger (less frequent) storm.

5.1.1 Design Frequency and Spread

Highway storm drainage provides safe passage for vehicles under a set of conditions called a design storm. The drainage system, including the curb and gutter and additional width such as parking lanes, conveys stormwater to pavement inlets to provide reasonable safety for traffic and pedestrians at a reasonable cost. As spread from the curb increases, the risk of traffic accidents increases because of hydroplaning and spray, along with nuisance to pedestrian, bicycle, and scooter traffic.

When specifying the AEP or return period for the design storm and the allowable spread during such a storm, designers make decisions regarding risk of accidents and traffic delays, and acceptable costs for the drainage system. Risk associated with water on traffic lanes increases with increasing traffic volume and traffic speed not only for safety reasons but also because of increased potential for delay. The safety of the public represents the primary consideration for designers in specifying the design frequency and design spread.

State and local Departments of Transportation (DOTs) establish design storm and spread criteria based on consideration of:

- Functional classification of the roadway, and possibly traffic volume within the functional classification.
- Traffic speed, which is a primary factor in hydroplaning when water is on the pavement.
- Existing and projected traffic volume, which may be an indicator of the economic importance of keeping the highway open to traffic. The costs of traffic delays and accidents increase with increasing traffic volumes.
- Cost. Balance between desirable and practicable criteria is sometimes necessary because of cost, and because of external factors such as constrained right-of-way (ROW) or utilities. The costs and feasibility of providing for a given design frequency and spread may vary significantly between projects. In some cases, it may be practicable to significantly

upgrade the drainage design and reduce risks at moderate costs. In other instances, costs may be very sensitive to the criteria selected for design.

Designers consider inconvenience, hazards, and nuisances to pedestrian, bicycle, and other personal transport traffic. In some places, such as in commercial areas, this consideration may assume major importance. Local design practice may also be a major consideration since it can affect the feasibility of designing to higher standards, and it influences public perception of acceptable practice.

Designers also consider the relative elevation of the highway and surrounding terrain where water can be drained only through a storm drainage system, as in underpasses and depressed roadway sections. They consider the potential for ponding to undesirable depths when selecting the frequency and spread criteria and in checking the design against storm runoff events of lesser frequency than the design event.

Selection of design criteria for intermediate types of facilities may be the most difficult. For example, some arterials with relatively high traffic volumes and speeds may not have shoulders which will convey the design runoff without encroaching on the traffic lanes. In these instances, practitioners typically assess the relative risks and costs of various design spreads to select appropriate design criteria. Table 5.1 provides example minimum design frequencies and spread based on the type of highway and traffic speed.

Along with the situations covered in Table 5.1, for depressed sections and underpasses where ponded water can be removed only through the storm drainage system, designers frequently consider additional criteria including a 0.02 AEP event. The use of a more severe event, such as a 0.01 AEP event to assess hazards at critical locations where water can pond to appreciable depths is commonly referred to as a “check storm.”

Table 5.1. Example minimum design frequency and spread.

Road Classification	Context	Design Frequency (AEP)	Design Spread
Interstate	Varies	0.02	Shoulder
Principal arterial (divided or bi-directional)	Design speed < 45 mph	0.1	Shoulder + 3 ft
	Design speed > 45 mph	0.1	Shoulder
	Sag vertical curve	0.02	Shoulder + 3 ft
Major or minor collector	Design speed < 45 mph	0.1	1/2 Driving Lane
	Design speed > 45 mph	0.1	Shoulder
	Sag vertical curve	0.1	1/2 Driving Lane
Local streets	Low ADT	0.2	1/2 Driving Lane
	High ADT	0.1	1/2 Driving Lane
	Sag Point	0.1	1/2 Driving Lane

5.1.2 Check Storm Frequency and Spread

Practitioners typically use a check storm any time runoff could cause severe flooding during less frequent (larger) events. Where ponding to undesirable depths could occur, as when a series of inlets terminates at a sag vertical curve, the designer checks the performance of gutters and inlets with an event more severe than the design event.

Designers base selection of the frequency for the check storm on the same considerations used to select the design storm, i.e., the consequences of spread exceeding that chosen for design and the potential for ponding. Where no significant ponding can occur, check storms are typically unnecessary. During the service life of a roadway, there is always a risk that a storm more severe than the design and check storm will occur once or multiple times. When the consequences of such events are potentially unacceptable, a designer may employ risk-based design concepts (FHWA 2016). With risk-based design, the designer evaluates the consequences of design flow exceedance and balances the number of occurrences of the consequences against cost and other goals of society.

Each State and locality determine standards for the criteria for spread during the check event. Examples of criteria for a check storm event include: 1) one lane open to traffic, and 2) one lane free of water. In the first, water may partially of fully cover the lane but at a depth that drivers can drive through at a reduced speed.

5.2 Surface Drainage

To facilitate surface drainage, designers avoid flat roadway surfaces. Slope may be parallel to the roadway, transverse to it, or both. The slope of the roadway in a longitudinal direction is the longitudinal grade. Designers refer to the overall vertical alignment of the roadway, including tangent grades and vertical curves, as the profile grade line. The longitudinal grade may represent the slope of the profile grade line, or along a designated offset, such as a gutter grade. Transverse slope is referred to as the “cross slope.”

When rain falls on a sloped pavement surface, it forms a thin film of water that increases in depth as it flows downgrade. Factors influencing the depth of water on the pavement include the length of the flow path, the texture of the pavement surface, the surface slope, and rainfall intensity. As the depth of water on the pavement increases, the potential for hydroplaning increases. Anderson et al. (1995) provides additional technical information on the mechanics of surface drainage. This section describes the following surface drainage topics:

- Hydroplaning.
- Longitudinal pavement slope.
- Cross or transverse pavement slope.
- Surface conveyance.
- Superelevation transition.
- Other surface features affecting drainage.

5.2.1 Hydroplaning

When a rolling vehicle tire meets a film of water on the roadway, it has the potential to lose contact with the roadway, a condition known as hydroplaning. Ideally, the water is channeled through the tire tread pattern and through the surface roughness of the pavement. Hydroplaning occurs when the drainage capacity of the tire tread pattern and the pavement surface is insufficient to conduct the water away, and the water begins to build up in front of the tire. As this wedge of water builds up in front of the tire, the wedge produces a force that can lift the tire off the pavement surface. This is considered as full dynamic hydroplaning and, since water offers no shear resistance, the tire loses its ability to exert stopping or steering force on the vehicle. The driver has then lost control of the vehicle. Hydroplaning can occur at speeds of 55 mph with a water depth of 0.08 inches (Anderson et al. 1995). However, depending on a variety of criteria, hydroplaning may occur at lower speeds and depths.

Hydroplaning is a function of the water depth, roadway geometry, vehicle speed, tread depth, tire inflation pressure, and pavement texture. The AASHTO Model Drainage Manual (AASHTO 2000) provides methods of calculating when it can occur. In problem areas, hydroplaning hazard may be reduced by:

- Designing the highway geometry to reduce the drainage path lengths of flow over the pavement to prevent flow buildup.
- Increasing the pavement surface texture depth. Grooving of concrete pavement and the use of asphalt-aggregate surface treatment (chip seal) are examples of surfaces that inhibit hydroplaning. An increase of pavement surface texture will increase the drainage capacity at the tire pavement interface.
- Using open graded asphaltic pavements. The open texture prevents the buildup of hydrostatic pressure and the corresponding lifting force by allowing the water to be forced out from under the tire.
- Adding drainage structures to capture water from the pavement to reduce the film of water and reduce the hydroplaning potential.

NASEM (2021) provides an in-depth discussion of hydroplaning and the related variables.

5.2.2 Longitudinal Grade

The AASHTO Policy on Geometric Design (AASHTO 2018) provides suggested minimum roadway longitudinal grades for safe pavement drainage on tangent grade sections. Based on its citation in 23 CFR 625.4, this Policy contains specific criteria and controls for the design of NHS projects. [See 23 CFR 625.3(b) and 625.4(a)]. In addition, to create safe roadways designers consider the following general statements:

- A minimum longitudinal gradient is more important for a curbed pavement than for an uncurbed pavement since the water is constrained by the curb. However, flat gradients on uncurbed pavements can lead to a spread problem if vegetation builds up along the pavement edge.
- Desirable gutter grades are greater than or equal to 0.5 percent for curbed pavements with an absolute minimum of 0.3 percent. Minimum grades can be maintained in very flat terrain by use of a rolling profile, or by warping the cross slope to achieve rolling gutter profiles (TxDOT 2019).
- To provide adequate drainage in sag vertical curves, a minimum slope of 0.3 percent is maintained within 50 ft of the low point of the curve. At the low point, the grade passes through zero. This is accomplished when the vertical curve constant, K, is equal to or less than 167 (50 in SI).

The vertical curve constant, K, is:

$$K = L / (G_2 - G_1) \tag{5.1}$$

where:

K	=	Vertical curve constant ft/percent (m/percent)
L	=	Horizontal length of curve, ft (m)
G_i	=	Grade of roadway, percent

Lessons from Experience: Avoiding Slippery Slopes

Designers may benefit from considering these lessons for specific situations:

- On highways where three or more lanes are sloped in the same direction, increase the cross slope of the lowest lanes. For example, slope the two lanes adjacent to the crown line at typical slope and increase the successive lanes, or portions of them, by 0.5 to 1 percent per lane, but not more than a total cross slope of 4 percent.
- When depressed medians are present, slope inside lanes toward the median if conditions warrant.
- Avoid introducing water from median areas to the travel lanes.
- Increase cross slopes in vertical curves where grade passes through zero and in flat sections where it is small.
- Slope shoulders to drain away from the pavement, except with raised, narrow medians and in superelevated curves. Shoulders with a greater cross slope than the roadway assist in reducing the depth of water in the travel lanes.

5.2.3 Cross (Transverse) Slope

The AASHTO Policy on Geometric Design of Highways and Streets specifies an acceptable range of cross slopes (AASHTO 2018). [See 23 CFR 625.3(b) and 625.4(a)]. Summarized in Table 5.2, these cross slopes balance the need for reasonably steep cross slopes for drainage and relatively flat cross slopes for driver comfort and safety. Cross slopes of 2 percent or less have little effect on driver effort in steering or on friction demand for vehicle stability (Gallaway et al. 1979). In areas of intense rainfall, a somewhat steeper cross slope (2.5 percent) may be used to facilitate drainage. When a designer considers deviating from values in Table 5.2, the AASHTO policy provides other information.

Table 5.2. Typical pavement cross slopes.

Surface Type *	Range in Rate of Surface Slope, ft/ft (m/m)
High-type surface (2-lanes)	0.015 - 0.020
High-type surface (3 or more lanes, each direction)	0.015 – 0.04 (increase 0.005 to 0.010 per lane)
Intermediate-type surface	0.015 - 0.030
Low-type surface	0.020 - 0.060
Bituminous or concrete shoulders	0.020 - 0.060
Shoulders with curbs	≥ 0.040

*High-, intermediate-, and low-type surfaces describe the relative heights of skid-resisting surface textural elements.

5.2.4 Surface Conveyance

Surface drainage includes conveyance features adjacent to the paved roadway that collects water from the pavement and carries it parallel to the roadway, although some surface drainage features may flow skewed from or perpendicular to the roadway. Parallel features include curb and gutter sections and median and roadside channels.

5.2.4.1 Curb and Gutter

Designers typically use curbs at the outside edge of pavements for low-speed highway facilities, and in some instances, adjacent to shoulders on moderate to high-speed facilities. Curbs serve several purposes:

- Contain surface runoff within the roadway and away from adjacent properties.
- Prevent erosion on fill slopes.
- Provide pavement delineation.
- Enable orderly development of adjacent property.
- Redirect errant vehicles back into the roadway.

Gutters formed in combination with curbs come in various widths. Gutters often have the same cross slopes as that of the pavement or they may have a steeper cross slope than the shoulder or adjacent lane (if present).

For stormwater runoff from cut slopes and other areas that drain toward the roadway, designers provide alternative drainage paths, where practical, to prevent such flow from entering the roadway. Where curbs are not needed for traffic purposes, shallow ditches at the edge of pavement offer advantages over curbed sections and provide channel capacity that is not dependent on spread on the pavement. Section 5.3 provides a detailed discussion of curb and gutter sections.

5.2.4.2 Roadside and Median Channels

Designers commonly use roadside channels with uncurbed roadway sections to convey runoff from the highway pavement and adjacent areas. Right-of-way limitations and access requirements often preclude the use of roadside channels on urban arterials. Designers typically use roadside channels in depressed roadway sections, and other locations with sufficient ROW and where driveways or intersections are infrequent.

To prevent runoff from median areas from running across the travel lanes, designers slope median areas and inside shoulders to a center swale. This design option is particularly useful for high-speed facilities and for facilities with more than two lanes of traffic in each direction. Chapter 6 provides a detailed discussion of roadside and median channels.

5.2.5 Other Surface Features Affecting Drainage

Other roadway surface features affect roadway drainage. These include bridge decks, median barriers, superelevated roadways, roundabouts, and porous pavements.

5.2.5.1 Bridge Decks

Design of bridge deck drainage addresses several challenges unique to the bridge environment in providing for and maintaining adequate drainage systems:

- Deck structural and reinforcing steel tends to corrode from deicing chemicals, so that designs focus on draining treated water to slow the corrosion.

- Water on bridge decks freezes before surface roadways leading to ice-covered bridges.
- Bridge deck drainage gutters may have lower capacity than roadway gutters because cross slopes may be flatter.
- Parapet-type bridge rails can accumulate roadway debris.
- Scuppers and other deck drains generally have smaller open areas than many roadway inlets and can be easily clogged by debris.
- Bridges lack auxiliary lanes or additional width beyond the travel lanes.
- Bridges over water may be subject to water quality restrictions limiting direct discharge to the water body.
- Bridges crossing over land, including other roadways or bridges, may have to convey water to a safe discharge location.

To address these difficulties in providing for deck drainage systems, designers focus on intercepting and redirecting gutter flow from the roadway leading to a bridge before it reaches a bridge whenever possible. For similar reasons, designers avoid zero longitudinal grades and sag vertical curves on bridges. HEC-21 includes detailed coverage of bridge deck drainage systems (FHWA 1993).

5.2.5.2 Median Barriers

When designing shoulder areas adjacent to median barriers, designers typically slope them toward the center to prevent drainage from running across the traveled pavement. Where designers use median barriers, they provide inlets or slotted drains to collect water accumulated against barriers at low points or where spread exceeds allowable on grade. For superelevated curves, designers provide inlets to collect water before it is redirected back to the roadway by the superelevated roadway geometry.

5.2.5.3 Superelevated Horizontal Curves

Designers can accomplish changes to the roadway direction in the horizontal plane by using circular curves. In many cases, horizontal curves involve super elevating the roadway to facilitate the safe passage of vehicles through a change in direction as shown in Figure 5.1. Superelevation is the transverse slope provided to reduce the tendency of a vehicle to overturn or to skid laterally outwards by raising the pavement outer edge with respect to inner edge.

As shown in Figure 5.1, the designer provides superelevation by steadily reducing the cross slope on the outer side of the curve until it is zero, and then steadily sloping the outer side of the roadway toward the inner side, until the inner side cross slope is continuous across the entire roadway. The designer steadily rotates the entire roadway further toward the inner side, until reaching the desired cross slope. The full superelevation cross slope depends on design speed and radius of curvature. State DOT design manuals provide maximum recommended values, for example, 8 percent in temperate areas where snow and ice are uncommon and 6 percent in areas where snow and ice are more common. Roadway designers commonly begin the transition from normal crown to superelevated section before the beginning of the horizontal curve, achieve full superelevation within the curve, and transition from superelevated back to normal crown.

Superelevation transitions present several challenges for drainage design:

- The increase in contributing pavement runoff when all lanes drain to the same side.
- The flat cross slope during the transition.
- Potential low or flat slope slopes in the longitudinal grade of the roadway gutter.

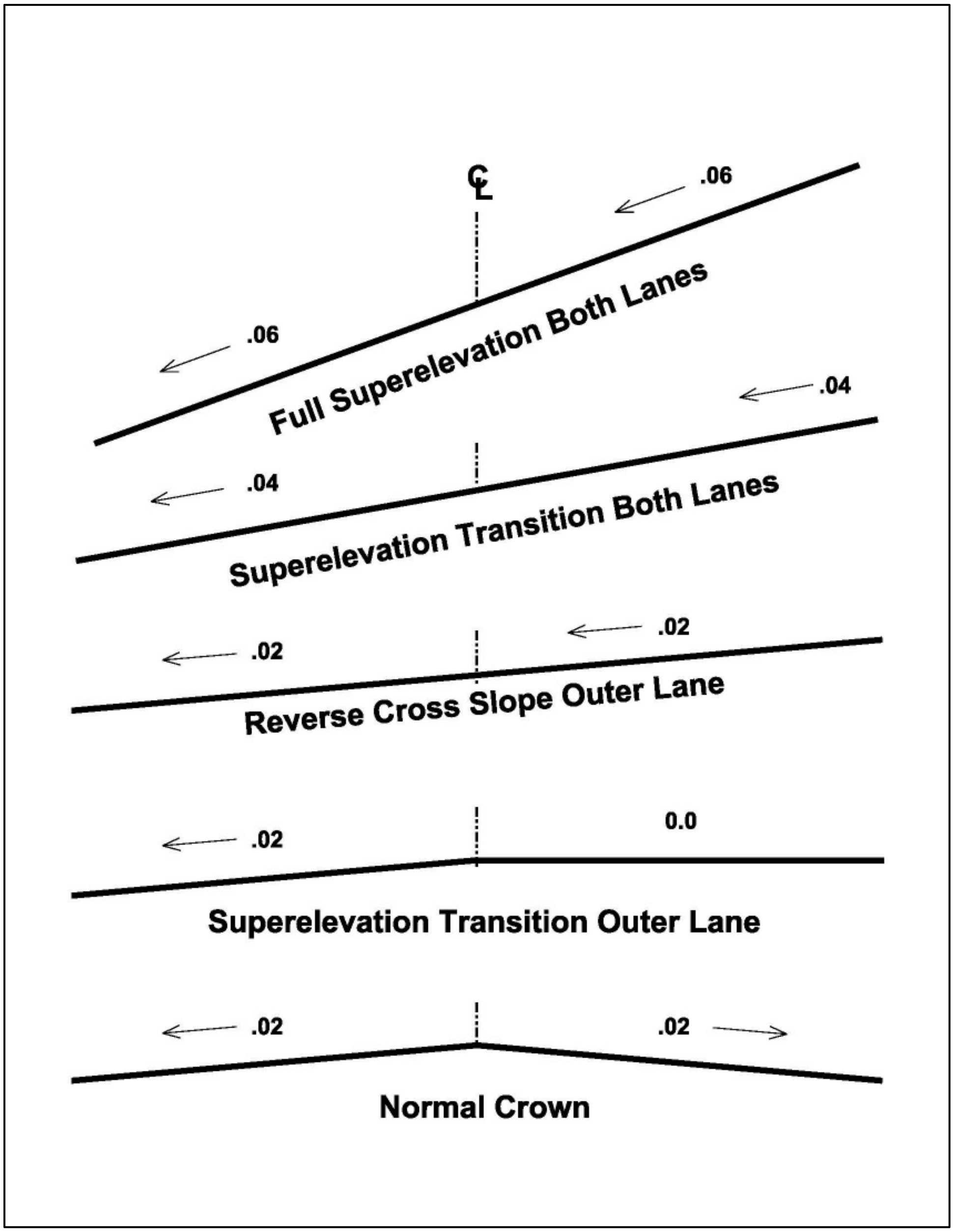

Figure 5.1 Transition from normal crown to superelevated curve to the left.

Fully superelevated sections present pavement drainage challenges by increasing the contributing drainage area to one side. The entire roadway section drains a single direction, rather than each half of the roadway draining toward its edge. The increased drainage length may be partially offset by increased cross slope in some cases. In addition to increasing the width of roadway draining to the edge, the curvature of the roadway causes the cross-roadway flow to converge from wide at the high, outer side to narrow at the low, inner side, increasing depth of surface flow.

The section of roadway where the cross slope in the right (outer) lane passes through zero is important for drainage design because ponding can occur and available head for inlets to remove water would also be zero. Flow in the roadway is then governed by longitudinal grade only. If there is no longitudinal grade in the same location as a zero cross slope water can build up on the pavement in that location. Designers seek to avoid conditions where water is directed across the roadway from the outer side of the curve to the inner side.

The drainage designer also considers the relative changes in the roadway profile grade and the gutter profile grade as these do not change at the same rates in a superelevation transition. Relative to the roadway profile grade, the gutter profile grade may decrease, increase, or even change direction. Depth of flow available at the curb may decrease and spread may increase (depending on flow direction).

In superelevation transitions, the roadway design may rotate the roadway cross-section about the centerline, inner edge, or outer edge. If rotated about the centerline or outer edge, the gutter profile on the inner side of the curve may be depressed by the increase of cross slope past the normal crown slope at full superelevation. Combining the increased drainage distance of a superelevated section and a depressed gutter profile grade line can result in significant increase in spread, and in depth of runoff on the inner side of curves. If the roadway is rotated about either edge, the centerline profile grade line will show a “hump” or “dip” to reflect the transition and curve that may affect drainage.

Because of the many possible situations for superelevation transitions and the importance of good drainage for safe roadways, drainage and roadway geometry designers coordinate to minimize problem areas created by superelevated curves and transitions. They consider the profile grade line, both gutter grades, and the rotation of the roadway (centerline, inner edge, or outer edge) in the superelevation transition to avoid flatter areas where water builds up and drains slowly from the roadway and to avoid areas where water is directed from one side of the road to the other.

5.2.5.4 Roundabouts

Designers increasingly use circular “roundabout” intersections as a traffic management technique. Roundabouts can present unique drainage situations. The profile grade lines of the roadways converging or crossing at a roundabout are adjusted to intersect at a common elevation at the center of the roundabout. Traffic turns to the right to enter the roundabout, curves to the left while traveling in the roundabout, turns to the right to exit the roundabout. Traffic proceeds through roundabouts at speeds lower than the approaching roadway sections. The lower speed facilitates the “reversing” motion of entering, transiting, and leaving the roundabout.

Typically, the central island of a roundabout is elevated, and roadways approaching a roundabout have a center crown with cross slopes of 0.02. The cross slope on the roundabout circle is an adverse superelevation (sloping from the outside of the curve rather than the inside) throughout (NASEM 2007, NASEM 2010). Researchers recommend that the central island be elevated in all classifications of roundabouts (mini, single-lane, and multi-lane). If the central island is not elevated, cross slope toward the central island will create ponding near the island, and drainage structures will be needed to alleviate the ponding (NASEM 2010). Multi-lane roundabouts, like other multi-lane features, exhibit wider pavement sections, and longer accumulation distances for runoff, than do single-lane features.

The adverse cross slope within the roundabout directs water toward the outside of the roundabout. Because the outer edge of the roadway within the roundabout has a larger circumference than the inner edge, as water flows toward the outer edge of the roundabout the increase of depth resulting from increasing pavement area is mitigated by the larger circumference.

Among the intended purposes of roundabouts is to limit traffic speed; because of this, they are inherently low-speed features. The tendency to limit speed also serves to mitigate hydroplaning, even in cases where water ponds on the pavement in depths greater than would be desirable on other roadway features.

Gutter design at the outer edge of the roundabout determines the spread conditions. The gutters either direct water to inlets within the roundabout or to gutters on roadways connected to the roundabout. Because roundabouts direct water to the periphery and slow traffic speeds, roundabouts can reduce the potential for hydroplaning compared to other intersection configurations.

5.2.5.5 Porous Pavement

Primarily to improve stormwater runoff quality, roadway designers sometimes use porous or permeable pavements that allow stormwater into the pavement so that it slowly runs through the pavement rather than quickly off over the pavement surface. Porous pavements do not generally affect stormwater runoff quantities for moderate to large design events because the quantity of water redirected through the pavement is small. However, there may be some quantity effect for smaller storms (Harvey and Smith 2018).

5.3 Flow in Gutters

A pavement gutter is a structure at the edge of the roadway that conveys water during a storm runoff event. It may include a portion or all of a travel lane. Figure 5.2 illustrates typical curb and gutter and shallow swale sections. Conventional curb and gutter sections commonly have a triangular shape with the curb forming the near-vertical leg of the triangle. Conventional gutters typically have a uniform cross slope (Figure 5.2, a.1), a composite cross slope (Figure 5.2, a.2), or a parabolic section (Figure 5.2, a.3). Shallow swale gutters typically have V-shaped or circular sections as illustrated in Figure 5.2 and are often used in paved median areas.

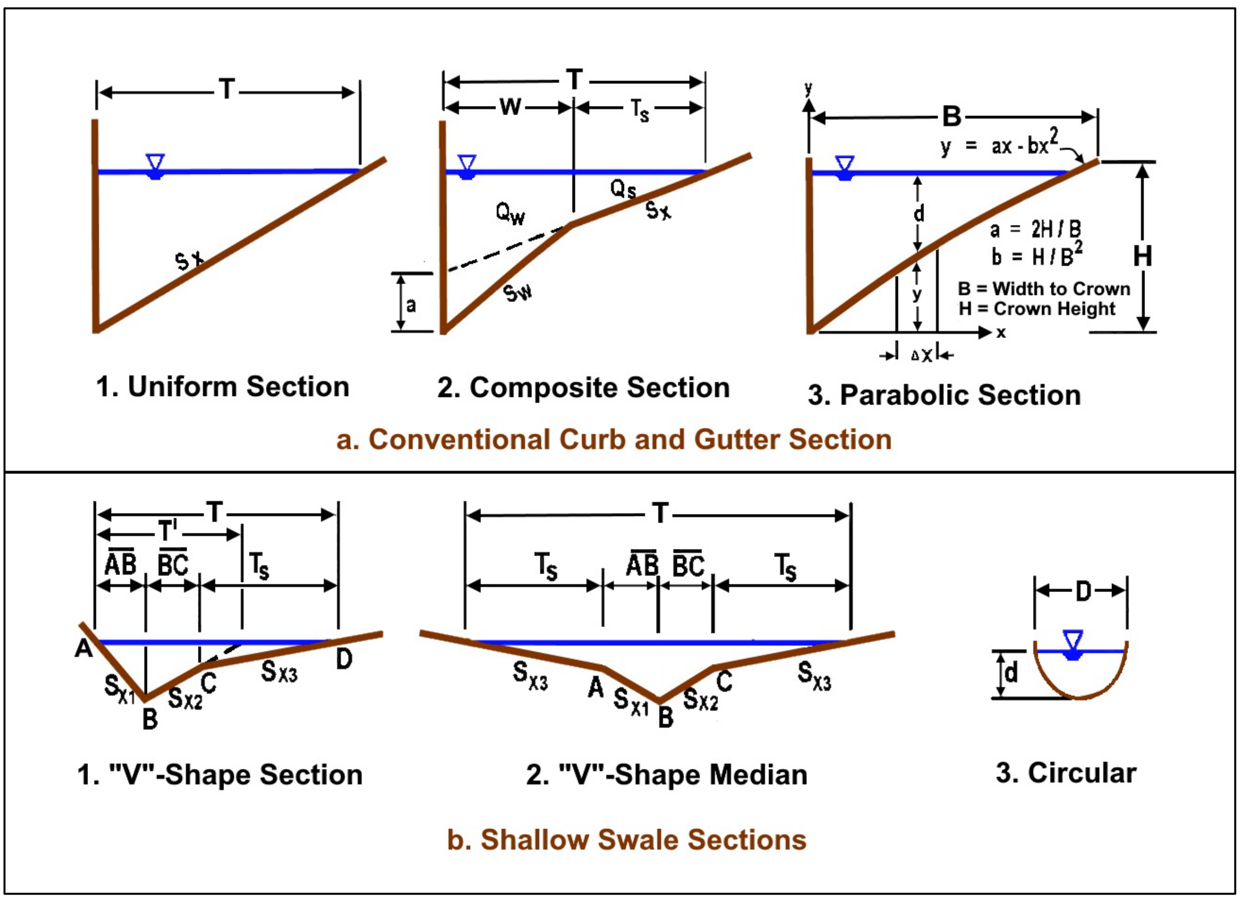

Figure 5.2. Typical stormwater conveyance sections.

5.3.1 Capacity Relationship

Gutter flow calculations estimate the spread of water on the shoulder, parking lane, or pavement section. Izzard stated that the hydraulic radius used in Manning's equation does not adequately describe the gutter cross-section, particularly where the top width of the water surface may be more than 40 times the depth at the curb, and modified Manning's equation for gutter flow (Izzard 1946):

$$Q = \frac{K_u}{n} S_x^{1.67} S_L^{0.5} T^{2.67} \tag{5.2}$$

where:

K_u	=	Unit conversion constant, 0.56 in CU (0.376 in SI)
n	=	Manning's coefficient
Q	=	Flow rate, ft^3/s (m^3/s)
T	=	Width of flow (spread), ft (m)
S_x	=	Cross slope, ft/ft (m/m)
S_L	=	Longitudinal grade, ft/ft (m/m)

Equation 5.2 neglects the resistance of the curb face since this resistance is negligible. Table 5.3 summarizes typical Manning's coefficients for paved gutters. In terms of velocity, the relationship is:

$$V = \frac{2K_u}{n} S_x^{0.67} S_L^{0.5} T^{0.67} \tag{5.3}$$

Designers often use spread on the pavement and flow depth at the curb as criteria for spacing pavement drainage inlets. Equation 5.2 can be solved in terms of T to estimate a spread width given a flow rate:

$$T = \left[\frac{Q\,n}{K_u\, S_x^{1.67}\, S_L^{0.5}} \right]^{0.375} \tag{5.4}$$

Table 5.3. Manning's n for street and pavement gutters (FHWA 1977).

Type of Gutter or Pavement	Manning's n *
Concrete gutter, troweled finish	0.012
Asphalt pavement: smooth texture	0.013
Asphalt pavement: rough texture	0.016
Asphalt pavement: smooth texture with concrete gutter	0.013
Asphalt pavement: rough texture with concrete gutter	0.015
Concrete pavement: float finished	0.014
Concrete pavement: broom finished	0.016

*For gutters with small slope, where sediment may accumulate, increase "n" by 0.002.

5.3.2 Conventional Curb and Gutter Sections

Conventional curb and gutter sections include a very short wall-like curb with a near-vertical face, and a toe section sloped upward to form the invert of the gutter. Gutters begin at the inside base of the curb and usually extend from the curb face toward the roadway centerline 1.0 to 3.0 ft. As illustrated in Figure 5.2, gutters can have uniform, composite, or curved sections; most commonly, they are uniform.

5.3.2.1 Uniform Cross Slope

Uniform gutter sections have a cross slope equal to the cross slope of the shoulder or travel lane adjacent to the gutter. Equations 5.2 and 5.3 describe the gutter flow characteristics in a uniform triangular gutter as illustrated in the following example.

Example 5.1:	Computation of triangular gutter flow.
Objective:	Estimate the spread given a flow rate of 1.8 ft^3/s (0.051 m^3/s) and find the gutter flow given a spread of 8.2 ft (2.5 m).

Given: Gutter section illustrated in Figure 5.2 (a.1).

S_L = 0.010 ft/ft (m/m)
S_x = 0.020 ft/ft (m/m)
n = 0.016

Step 1. Compute spread, T, using equation 5.4.

$T = [(Q\ n)/(K_u\ S_x^{1.67}\ S_L^{0.5})]^{0.375} = [(1.8)(0.016)/\{(0.56)(0.020)^{1.67}(0.010)^{0.5}\}]^{0.375} = 9.0$ ft

Step 2. Compute Q using equation 5.2.

$Q = (K_u/n)\ S_x^{1.67}\ S_L^{0.5}\ T^{2.67} = (0.56/0.016))(0.020)^{1.67}(0.010)^{0.5}\ (8.2)^{2.67} = 1.4\ ft^3\ /s$

Solution:	The spread given a flow rate of 1.8 ft^3/s (0.051 m^3/s) is 9.0 ft (2.7 m). The gutter flow given a spread of 8.2 ft (2.5 m) is 1.4 ft^3/s (0.040 m^3/s).

5.3.2.2 Composite Gutters

Gutters with composite sections are depressed in relation to the adjacent pavement slope. Most commonly, designers use gutters with composite sections as the flow approaches a storm drain inlet. Depressed gutters can present a hazard to bicycle traffic.

Because the cross-section is no longer a simple triangle, the total flow is conceptually divided between the flow in the depressed section, Q_w, and the flow in the side section, Q_s. Based on the composite channel geometry, the fraction of the flow in the depressed and side sections are represented as:

$$Q_w = Q\ E_o \tag{5.5}$$

$$Q_s = Q\ (1-E_o) \tag{5.6}$$

where:

Q	=	Total gutter flow rate, ft^3/s (m^3/s)
Q_w	=	Flow in the depressed section of the gutter, ft^3/s (m^3/s)
Q_s	=	Flow in the gutter section above the depressed section, ft^3/s (m^3/s)
E_o	=	Ratio of flow in the depressed section (usually the width of a grate) to total gutter flow

The ratio of flow in the depressed section to the total flow is:

$$E_o = \frac{1}{1 + \dfrac{S_w / S_x}{\left(1 + \dfrac{S_w / S_x}{(T / W) - 1}\right)^{2.67} - 1}} \qquad (5.7)$$

where:

S_w	=	Cross slope in the depressed section, ft/ft (m/m)

As shown in Figure 5.2 (a.2) the depressed section cross slope is:

$$S_w = S_x + \frac{a}{W} \qquad (5.8)$$

The following example demonstrates computing flow and spread in a composite gutter.

Example 5.2: Composite gutter flow.

Objective: Estimate: A) the flow in a composite gutter at a spread of 8.2 ft (2.5 m) and B) the spread in the gutter at a flow of 4.2 ft^3/s (0.12 m^3/s).

Given: Gutter section illustrated in Figure 5.2 (a.2) with:

W	=	2 ft (0.61 m)
S_L	=	0.01 ft/ft (m/m)
S_x	=	0.02 ft/ft (m/m)
n	=	0.016
a	=	2 inches (51 mm) (gutter depression)

Step A1. Compute the cross slope of the depressed gutter, S_w, and the width of spread from the junction of the gutter and the road to the limit of the spread, T_s.

S_w = a / W + S_x = [(2)/(12)]/(2) + (0.020) = 0.103 ft/ft

T_s = T - W = 8.2 - 2.0 = 6.2 ft

Step A2. Compute Q_s from equation 5.2 using T_s.

$Q_s = (K_u/n)\, S_x^{1.67}\, S_L^{0.5}\, T_s^{2.67} = (0.56/0.016)\,(0.02)^{1.67}\,(0.01)^{0.5}\,(6.2)^{2.67} = 0.66\ ft^3/s$

Step A3. Determine the gutter flow, Q.

T / W = 8.2 / 2 = 4.10

S_w / S_x = 0.103 / 0.020 = 5.15

Using equation 5.7:

$$E_o = \frac{1}{1 + \dfrac{S_w / S_x}{\left(1 + \dfrac{S_w / S_x}{(T/W) - 1}\right)^{2.67} - 1}} = \frac{1}{1 + \dfrac{5.15}{\left(1 + \dfrac{5.15}{(4.10) - 1}\right)^{2.67} - 1}} = 0.7$$

Using equation 5.6:

$Q = Q_s / (1 - E_o) = 0.66 / (1 - 0.70) = 2.3$ ft^3/s

Step B1. Select an initial estimate of Q_s.

There is not a direct computational solution for estimating spread from flow in a composite gutter, therefore, an iterative approach is used. Select an initial estimate of $Q_s = 1.4$ ft^3/s.

Step B2. Compute Q_w.

$Q_w = Q - Q_s = 4.2 - 1.4 = 2.8$ ft^3/s

Step B3. Determine W/T ratio.

$E_o = Q_w / Q = 2.8 / 4.2 = 0.67$

$S_w / S_x = 0.103 / 0.020 = 5.15$

Solve for T/W using equation 5.7:

$$0.67 = \frac{1}{1 + \dfrac{5.15}{\left(1 + \dfrac{5.15}{(T/W) - 1}\right)^{2.67} - 1}}$$

T/W = 4.48

Step B4. Compute spread based on the assumed Q_s.

T = W (T/W) = 2.0 (4.48) = 9.0 ft

Step B5. Compute T_s.

$T_s = T - W = 9.0 - 2.0 = 7.0$ ft

Step B6. Use equation 5.2 to determine Q_s for computed T_s .

$Q_s = (K_u/n)\, S_x^{1.67}\, S_L^{0.5}\, T^{2.67} = (0.56/0.016)\,(0.02)^{1.67}\,(0.01)^{0.5}\,(7.0)^{2.67} = 0.92$ ft^3/s

Step B7. Compare computed Q_s with assumed Q_s.

Q_s assumed = 1.4 > 0.92, Computed Q_s not close to assumed. Try again.

Step B8. Try a new assumed Q_s and repeat steps B1 through B7.

Assume $Q_s = 1.85$ ft^3/s

$Q_w = 4.2 - 1.85 = 2.35$ ft^3/s

$E_o = Q_w / Q = 2.35 / 4.2 = 0.56$

$S_w / S_x = 5.15$

$T / W = 5.55$

$T = 2.0 (5.55) = 11.1$ ft

$T_s = 11.1 - 2.0 = 9.1$ ft

$Q_s = 1.85$ ft^3/s

Q_s assumed = Q_s computed. Computations completed.

Solution:	A) The estimated discharge of the gutter for the given spread is 2.3 ft^3/s (0.065 m^3/s). B) The estimated spread of the composite gutter for the given discharge is 11.1 ft (3.38 m).

5.3.2.3 Gutters with Curved Sections

Older city streets or highways with curved pavement sections sometimes have curved gutter sections. Where the pavement cross-section is curved, gutter capacity varies with the configuration of the pavement. For this reason, discharge-spread or discharge-depth-at-the-curb relationships developed for one pavement configuration do not apply to another section with a different crown height or half width. Appendix B includes procedures for developing conveyance curves for parabolic pavement sections.

5.3.3 Shallow Swale Sections

Where traffic control does not demand curbs, designers typically use a small swale section of circular or V-shape to convey runoff from the pavement. For example, designers use swales to convey runoff from pavement on fills to protect the embankment from erosion. Small swale sections may have sufficient capacity to convey the flow to a location suitable for interception.

5.3.3.1 V-Sections

Equation 5.2 can be used to compute the flow in a shallow V-shaped section by estimating the cross slope, S_x, using the following equation:

$$S_x = \frac{S_{x1} S_{x2}}{S_{x1} + S_{x2}} \tag{5.9}$$

The following example demonstrates the analysis of a V-shaped shoulder gutter.

Example 5.3:	V-shaped roadside shoulder gutter.
Objective:	Find spread for a design flow of 1.77 ft^3/s (0.050 m^3/s).

Given: V-shaped roadside gutter (Figure 5.2 (b.1)) with:

S_L	=	0.01 ft/ft (m/m)
S_{x1}	=	0.25 ft/ft (m/m)
S_{x3}	=	0.02 ft/ft (m/m)
n	=	0.016
S_{x2}	=	0.04 ft/ft (m/m)
T_{BC}	=	2.0 ft (0.61 m)

Step 1. Calculate S_x using equation 5.8 assuming all flow is contained entirely in the V-shaped gutter section determined by S_{x1} and S_{x2}.

$S_x = S_{x1} S_{x2} / (S_{x1} + S_{x2}) = (0.25) (0.04) / (0.25 + 0.04) = 0.0345$ ft/ft

Step 2. Using equation 5.4, find the hypothetical spread, T', assuming all flow contained entirely in the V-shaped gutter.

$T' = [(Q\ n)/(K_u\ S_x^{1.67}\ S_L^{0.5})]^{0.375} = [(1.77)(0.016)/\{(0.56)(0.0345)^{1.67}(0.01)^{0.5}\}]^{0.375} = 6.4$ ft

Step 3. Determine if T' is within S_{x1} and S_{x2}.

$d_B = T_{BC}\ S_{x2} = (2)\ (0.04) = 0.08$ ft

$T_{AB} = d_B\ /\ S_{x1} = (0.08)\ /\ (0.25) = 0.32$ ft

$T_{AC} = T_{AB} + T_{BC} = 0.32 + 2.0 = 2.32$ ft

2.32 ft < T' therefore, spread falls outside V-shaped gutter section. An iterative solution technique is used to solve for the section spread, T, as illustrated in the following steps.

Step 4. Solve for the depth at point C, y_c, and compute an initial estimate of the spread along T_{BD}.

$y_C = d_B - T_{BC}\ (S_{x2})$

From the geometry of the triangle formed by the gutter, an initial estimate for d_B is determined as:

$(d_B\ /0.25) + (d_B\ /0.04) = 6.4$ ft

$d_B = 0.22$ ft

$y_c = 0.22 - (2.0)\ (0.04) = 0.14$ ft

$T_s = y_c\ /\ S_{x3} = 0.14/\ 0.02 = 7$ ft

$T_{BD} = T_s + T_{BC} = 7 + 2 = 9$ ft

Step 5. With T_{BD}, develop a weighted slope for S_{x2} and S_{x3}.

2.0 ft at S_{x2} (0.04) and 7.0 ft at S_{x3} (0.02)

$[(2.0)\ (0.04) + (7.0)\ (0.02)]\ /\ 0.90 = 0.024$ ft/ft

Use this slope along with S_{X1}, find S_x using equation 5.9:

$S_x = (S_{x1}\ S_{x2})\ /\ (S_{x1} + S_{x2}) = [(0.25)\ (0.024)]\ /\ (0.25 + 0.024) = 0.022$ ft/ft

Step 6. Using equation 5.2, compute the gutter spread using the composite cross slope, S_x.

$T = [(Q\ n)/(K_u\ S_x^{\ 1.67}\ S_L^{\ 0.5})]^{\ 0.375} = [(1.77)(0.016)/\{(0.56)(0.022)^{1.67}(0.01)^{0.5}\}]^{0.375} = 8.5$ ft

This 8.5 ft is lower than the assumed value of 9.0 ft.

Therefore, assume $T_{BD} = 8.3$ ft and repeat step 5 and step 6.

Step 5 (repeated). 2.0 ft at S_{x2} (0.04) and 6.3 ft at S_{x3} (0.02).

$[(2.0)\ (0.04) + (6.3)\ (0.02)]\ /\ 8.30 = 0.0248$

Use this slope along with S_{X1}, find S_x using equation 5.6:

$S_x = [(0.25)\ (0.0248)]\ /\ (0.25 + 0.0248) = 0.0226$ ft/ft

Step 6 (repeated). Using equation 5.2 compute the spread.

$T = [(Q\ n)/(K_u\ S_x^{1.67}\ S_L^{0.5})]^{0.375} = [(1.77)(0.016)/\{(0.56)(0.0226)^{1.67}(0.01)^{0.5}\}]^{0.375} = 8.31$ ft

Solution: This value of T is close to the assumed value, therefore, OK.

The following example illustrates analysis of a V-shaped median gutter resulting from a roadway with an inverted crown section.

Example 5.4:	V-shaped median shallow swale.
Objective:	Find A) spread for the design flow of 24.7 ft^3/s (0.70 m^3/s) and B) compute the flow for a spread of 23.0 ft (7.0 m).

Given: V-shaped gutter as illustrated in Figure 5.2 (b.2) with:

T_{AB}	=	3.28 ft (1 m)
T_{BC}	=	3.28 ft (1 m)
S_L	=	0.01 ft/ft (m/m)
n	=	0.016
S_{x1}	=	0.25 ft/ft (m/m)
S_{x2}	=	0.25 ft/ft (m/m)
S_{x3}	=	0.04 ft/ft (m/m)

Step A1. Assume spread remains within middle "V" (A to C) and compute S_x.

$S_x = (S_{x1} S_{x2}) / (S_{x1} + S_{x2}) = (0.25)(0.25) / (0.25 + 0.25) = 0.125$ ft/ft

Step A2. Compute the spread from equation 5.4.

$T = [(Q\,n)/(K_u\, S_x^{1.67}\, S_L^{0.5})]^{0.375} = [(24.7)(0.016)/\{(0.56)(0.125)^{1.67}(0.01)^{0.5}\}]^{0.375} = 7.65$ ft

Since "T" is outside S_{x1} and S_{x2} an iterative approach is used to compute the spread.

Step A3. Treat one-half of the median gutter as a composite section and solve for T' equal to one-half of the total spread.

Q' for T' = ½ Q = 0.5 (24.7) = 12.4 ft^3/s

Step A4. Try $Q'_s = 1.8\ ft^3/s$.

$Q'_w = Q' - Q'_s = 12.4 - 1.8 = 10.6\ ft^3/s$

Step A5. Using equation 5.5, determine the W/T' ratio.

$E'_o = Q'_w/Q' = 10.6/12.4 = 0.85$

$S_w / S_x = S_{x2} / S_{x3} = 0.25 / 0.04 = 6.25$

W/T' = 0.33 from trial-and-error

Step A6. Compute spread based on assumed Q'_s.

T' = W / (W/T') = 3.28 / 0.33 = 9.94 ft

Step A7. Compute T_s based on assumed Q'_s.

$T_s = T' - W = 9.94 - 3.28 = 6.66$ ft

Step A8. Use equation 5.2 to determine Q'_s for T_s.

$Q'_s = (K_u/n)\, S_{x3}^{1.67}\, S_L^{0.5}\, T_s^{2.67} = (0.56/0.016)(0.04)^{1.67}(0.01)^{0.5}(6.66)^{2.67} = = 2.56\ ft^3/s$

Step A9. Check computed Q'_s with assumed Q'_s.

Q'_s assumed = 1.8 < 2.56 = Q'_s computed

Therefore, try a new assumed Q'_s and repeat steps 4 through 9.

Assume Q'_s = 0.04

Q'_w = 12.0 ft^3/s

E'_o = 0.97

S_w/S_x = 6.25

W/T' = 0.50 by iteration, as in example 5.2 (step 6)

T' = 6.56 ft

T_s = 1.0 ft

Q_s = 0.39 ft^3/s

Q_s computed = 0.39 close to 0.40 = Q_s assumed, therefore OK.

T = 2 T' = 2 (6.56) = 13.12 ft

Step B1. Compute half-section top width.

Analyze in half-section using composite section techniques. Double the computed half width flow rate to get the total discharge:

T' = T/2 = 23 / 2 = 11.5 ft

T_s = T' - 3.28 = 8.22 ft

Step B2. Determine Q_s.

Using equation 5.2:

$Q_s = (K_u/n)\ S_x^{1.67}\ S_L^{0.5}\ T_s^{\ 2.67} = (0.56/0.016)\ (0.04)^{1.67}\ (0.01)^{0.5}\ (8.22)^{2.67}$ = 4.56 ft^3/s

Step B3. Determine flow in half-section.

T'/W = 11.5/ 3.28 = 3.5 1

S_w / S_x = 0.25 / 0.04 = 6.25

$E_o = 1 / \{1 + (S_w/S_x) / [(1 + (S_w/S_x) /(T'/W - 1))^{2.67} - 1]\}$

$= 1 / \{1 + (6.25) / [(1 + (6.25) /(3.5 - 3.28))^{2.67} - 1]\}$

$= 0.814 = Q'_w / Q = 1 - Q'_s / Q'$

$Q' = Q'_s / (1 - 0.814) = 4.56 / (1 - 0.814)$ = 24.5 ft^3/s

Q = 2 Q' = 2 (24.5) = 49 ft^3/s

Solution: A: Estimated spread is 13.12 ft (4.0 m). B: Estimated flow is 49 ft^3/s (1.4 m^3/s).

5.3.3.2 Circular Sections

Flow in shallow circular gutter sections can be represented by the relationship:

$$\frac{d}{D} = K_u\left[(Qn)/\left(D^{2.67}S_L^{0.5}\right)\right]^{0.488} \tag{5.10}$$

where:

d	=	Depth of flow in circular gutter, ft (m)
D	=	Diameter of circular gutter, ft (m)
K_u	=	Unit conversion constant, 0.972 in CU (1.179 in SI)

The width of circular gutter section T_w is represented by the chord of the arc which can be computed using:

$$T_W = 2\left(r^2 - (r - d)^2 \right)^{0.5} \tag{5.11}$$

where:

T_w	=	Width of circular gutter section, ft (m)
r	=	Radius of circular gutter, ft (m)

Example 5.5:	Circular channels.
Objective:	Find flow depth and top width of a circular gutter.

Given: A circular gutter swale as illustrated in Figure 5.2, b.3 with:

D	=	4.92 ft (1.5 m)
S_L	=	0.01 ft/ft (m/m)
n	=	0.016
Q	=	17.6 ft^3/s (0.50 m^3/s)

Step 1. Determine flow depth.

Use equation 5.10:

$d/D = K_u\, [(Q\ n)/ (D^{2.67}\ S_L^{0.5})]^{0.488} = (0.972)\ [((17.6)\ (0.016))/ ((4.92)^{2.67}\ (0.01^{0.5})]^{0.488} = 0.20$

$d = D\ (d/D) = 4.92(0.20) = 0.98$ ft

Step 2. Using equation 5.11, determine T_w.

$T_w = 2\ [r^2 - (r - d)^2]^{1/2} = 2\ [(2.46)^2 - (2.46 - 0.98)^2]^{1/2} = 3.93$ ft

Solution:	Estimated depth is equal to 0.98 ft (0.3 m) and estimated top width is 3.93 ft (1.2 m).

5.3.4 Flow in Sag Vertical Curves

As gutter flow approaches the low point in a sag vertical curve, the flow can exceed the allowable design spread values because of the continually decreasing gutter slope. Check the spread in these areas to ensure it remains within allowable limits. If the computed spread exceeds design values, additional inlets can be provided to reduce the flow as it approaches the low point. Chapter 7 discusses sag vertical curves and measures for reducing spread in more detail.

In vertical curve cases where a negative grade goes to a lesser (flatter) grade, spread may increase because conveyance in the gutter decreases.

5.3.5 Relative Flow Capacities

Examples 5.1 and 5.2 illustrate the advantage of a composite gutter section. The capacity of the section with a depressed gutter in the examples is 70 percent greater than that of the section with a straight cross slope with all other parameters held constant.

Equation 5.2 can be used to examine the relative effects of changing the values of spread, cross slope, and longitudinal slope on the capacity of a section with a straight cross slope.

To examine the effects of cross slope on gutter capacity, equation 5.2 can be transformed as follows into a relationship between S_x and Q. Let:

$K_1 = n / (K_u S_L^{0.5} T^{2.67})$

Then,

$S_x^{1.67} = K_1 Q$

and

$$\left(\frac{S_{x1}}{S_{x2}}\right)^{1.67} = \frac{K_1 Q_1}{K_2 Q_2} = \frac{Q_1}{Q_2} \tag{5.12}$$

Similar transformations can be performed to evaluate the effects of changing longitudinal slope and width of spread on gutter capacity resulting in:

$$\left(\frac{S_{L1}}{S_{L2}}\right)^{0.5} = \frac{Q_1}{Q_2} \tag{5.13}$$

$$\left(\frac{T_1}{T_2}\right)^{2.67} = \frac{Q_1}{Q_2} \tag{5.14}$$

Figure 5.3 illustrates that the effects of cross slope are also relatively significant. At a cross slope of 4 percent, a gutter has 10 times the capacity of a gutter of 1 percent cross slope. A gutter at 4 percent cross slope has 3.2 times the capacity of a gutter at 2 percent cross slope. Designers generally have little latitude to vary longitudinal slope to increase gutter capacity but slope changes, which change gutter capacity, are frequent.

5.3.6 Gutter Flow Time

The flow time in gutters is an important component of the time of concentration for the contributing drainage area to an inlet. To find the gutter flow component of the time of concentration, a method for estimating the average velocity in a reach of gutter is needed. The velocity in a gutter varies with the flow rate and the flow rate varies with the distance along the gutter, i.e., both the velocity and flow rate in a gutter are spatially varied. Designers can estimate the time of flow using an average velocity obtained by integration of the Manning's equation for the gutter section with respect to time (see Appendix B for the derivation):

$$V_a = K_u\ K_G \left[\left(T_2^{2.67} - T_1^{2.67}\right) / \left(T_2^2 - T_1^2\right)\right] \tag{5.15}$$

where:

V_a	=	Average velocity in the gutter section between T_1 and T_2 locations, ft/s (m/s)
T_1	=	Upstream spread, ft (m)
T_2	=	Downstream spread, ft (m)
K_G	=	Gutter geometry parameter
K_u	=	Unit conversion constant, 0.84 in CU (0.564 in SI)

The gutter geometry parameter is:

$$K_G = (S_L^{0.5} S_X^{0.67}) / n \tag{5.16}$$

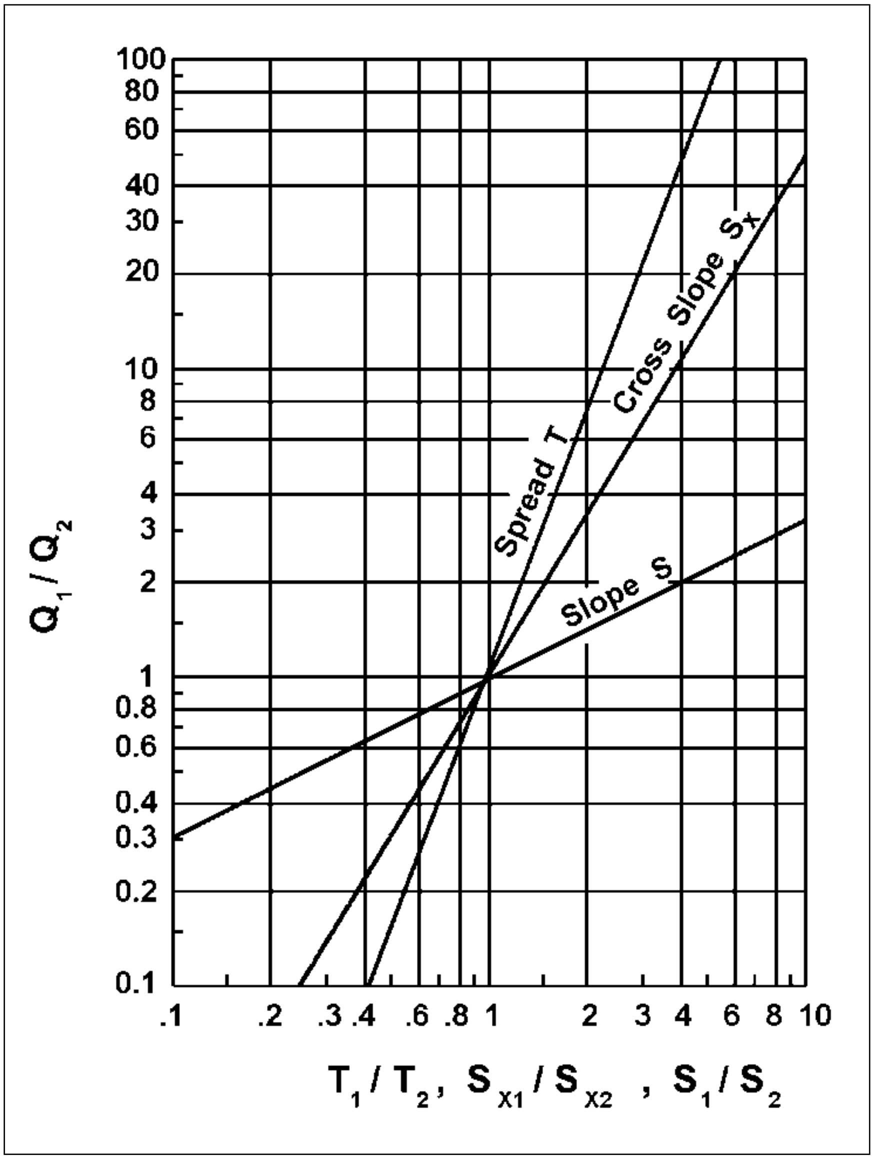

Figure 5.3. Relative effects of spread, cross slope, and longitudinal slope on gutter capacity.

Example 5.6:	Gutter flow time.
Objective:	Find the travel time in the gutter for an inlet spacing of 330 ft (100 m).

Given: A triangular gutter section:

T_1	=	3.28 ft (1.0 m)
T_2	=	9.84 ft (3.0 m)
S_L	=	0.03 ft/ft (m/m)
S_x	=	0.02 ft/ft (m/m)
n	=	0.016

Step 1. Compute the gutter geometry parameter.

Use equation 5.16:

$K_G = (S_L^{0.5}\ S_x^{0.67}) / n = (0.03^{0.5}\ 0.02^{0.67}) / 0.016 = 0.79$

Step 2. Estimate the average velocity in the gutter.

Use equation 5.15:

$V_a = K_u K_G [(T_2^{2.67} - T_1^{2.67}) / (T_2^2 - T_1^{2.})] = (0.83)(0.79) [((9.84)^{2.67} - (3.28)^{2.67}) / ((9.84)^2 - (3.28)^{2.})]$

$= 3.22$ ft/s

Step 3. Estimate the travel time in the gutter.

t = L/V = 330 / 3.22 / 60 = 1.7 min

Solution: Travel time in the gutter between the two spread locations is 1.7 minutes.