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Addendum to the Storm Water Management Model Reference Manual

Volume II –Hydraulics



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Addendum to the Storm Water Management Model Reference Manual Volume II – Hydraulics

by

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Abstract

SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. This document describes the additional modeling features that have been added into SWMM's hydraulic model because the original publication of the SWMM Reference Manual Volume II – Hydraulics (May 2017). This addendum covers the addition of a Preissmann Slot option, new features for modeling street runoff capture by inlet drains, a Type 5 variable speed pump, and additional Storage Curve options to SWMM.

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1. Preissmann Slot

Chapter 3 of the SWMM Hydraulics Reference Manual (Rossman, 2017) describes how the full dynamic wave solution for unsteady flow in a conveyance network is computed. In that procedure, when a network node becomes surcharged resulting in pressurized flow, the normal method of updating the hydraulic head at the node is replaced by the so-called Surcharge Algorithm. The assumptions of this algorithm have been questioned (Yen, 2001) and it can experience numerical instability in the transition between open-channel and pressurized flow.

As an alternative to the surcharge algorithm, SWMM can utilize the more widely accepted Preissmann Slot Method (Cunge and Wegner, 1964) for handling pressurized flow in closed conduits. In this case, the conduit's cross-section is assumed to have a narrow open slot at the top along its entire length. This permits the water level in the conduit to exceed its full depth while only slightly increasing its flow area. It thus becomes possible to compute a surface area contribution to the conduit's end nodes once it reaches full depth. As a result, SWMM is able to continue to use its regular solution for updating nodal heads under all flow conditions without having to resort to the surcharge algorithm.

In theory, the width of the slot should be determined by having the celerity of an open channel gravity wave equal to the speed of a pressure wave affected by the compressibility of the elastic pipe wall. This would result in a slot width w_{slot} equal to:

$$w_{slot} = gA/c^2 \tag{1}$$

where g is the acceleration of gravity, A is the conduit's cross-sectional area when full and c is the speed of the pressure wave. The latter quantity depends on the conduit's diameter, wall thickness, and modulus of elasticity and typically ranges from a few hundred to several thousand ft/sec (Yen, 2001).

Some care is needed in choosing a slot width because too large a value will result in reduced accuracy while too small a value can cause numerical instabilities. There is also the issue of maintaining a smooth transition between almost full flow and slot flow. The choice used by SWMM is a modified version of a formula proposed by Sjőberg (1982) and is given by:

$$w_{slot}/W_{max} = .0523\exp(-(Y/Y_{full})^{2.4}) \tag{2}$$

where W_{max} is the conduit's maximum width, Y_{full} is its full depth, and Y is depth of flow. This equation applies to Y/Y_{full} values between 0.985257 and 1.7. Below this range the slot is not used, while above it the slot width relative to W_{max} is fixed at 0.01 or 1 percent. The range's lower limit was chosen so that the width computed from Equation 2 is the same as the width across a circular pipe at that flow depth. This helps produce a smooth transition between open channel and pressurized flow regimes.

When the slot method is employed, for computational purposes the flow depth in a closed conduit is allowed to exceed its physical full depth. When it reaches the limit at which the slot formula applies, the resulting water surface width is used to compute the surface area that the conduit contributes to SWMM's regular head updating formula at its end nodes. It also contributes to the conduit's flow area when it rises above the full depth. It is not used when computing the conduit's hydraulic radius.

2. Street Cross-Sections

SWMM defines the geometry of a street or roadway cross-section as a special case of the irregular channel discussed in Section 5.3 of the SWMM Hydraulics Reference Manual (Rossman, 2017). The shape of a one-sided street cross-section is shown in Figure 1. In its most basic form it consists of a road surface with downward slope S_x extending a distance of T_{crown} to a vertical curb of height H_{curb}. To this can be added:

- an optional depressed gutter section of width W that extends to a depth "a" below the normal curb height
- an optional backing section extending beyond the curb a distance T_{back} that rises at a slope of S_{back}.

A two-sided street cross-section adds a mirror image of the one-sided street to the right of the street crown with the same roadway, gutter, curb, and backing dimensions.

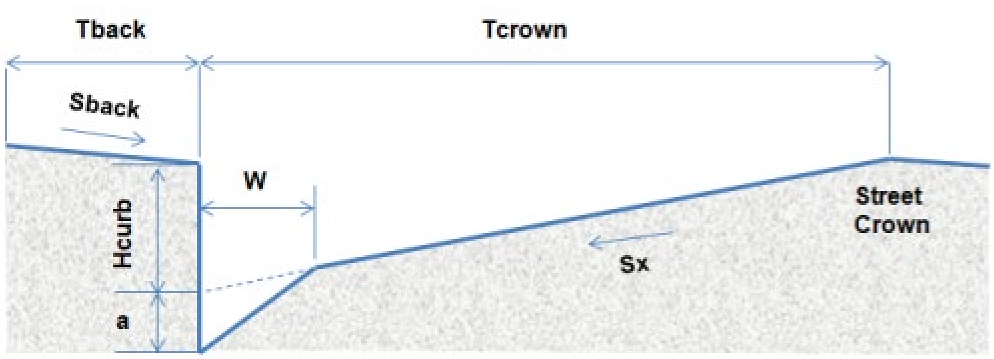


Figure 1. A one-sided street cross-section (not to scale)

Street cross-sections use the same procedures as irregular channel transects to compute tables of flow area, top width, and hydraulic radius at 50 equally spaced increments of flow depth (for both one-sided and two-sided streets). The 50 equally spaced increments are the same as the increments for SWMM Transects. This requires that in addition to the dimensions shown in Figure 1, a Manning's roughness coefficient must be specified for the road surface and for the backing surface, if present.

3. Storage Unit Geometry

SWMM's hydraulic modeling procedures require knowledge of how a storage unit's surface area A and volume V vary with surface depth Y above the bottom of the unit. It is sufficient to specify either an area or volume relationship with respect to depth because one can be derived from the other ($A = dV/dY$ and $V = \int AdY$). SWMM uses surface area to describe a storage unit's shape. One can select either from several standard shapes where A is a quadratic function of Y, from a general power law relation between A and Y or use a tabular listing of Y and A values.

3.1 Standard Storage Shapes

SWMM supports several common storage unit shapes, listed in Table 1, whose top surface area A can be expressed as a quadratic function of height Y:

$$A = a_0 + a_1 Y + a_2 Y^2 \tag{3}$$

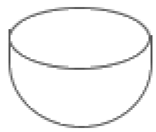
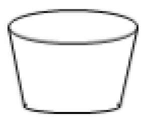
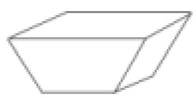
The constants a_0, a_1, and a_2 depend on the shape's dimensions as shown in Table 1.

Dynamic wave analysis requires specification of volume V varies with depth Y. Integrating Equation 3 over depth yields:

$$V = a_0 Y + (a_1/2)Y^2 + (a_2/3)Y^3 \tag{4}$$

Kinematic wave analysis requires specification of the depth associated with a given volume. For a cylindrical shape: $Y = V/a_0$, while for paraboloid shape: $Y = \sqrt{2V/a_1}$. For the other shapes the cubic Equation 4 is solved numerically for Y given V using the Newton-Raphson-Bisection method over the interval [0, Y_{full}] with initial estimate $Y = V/a_0$, convergence tolerance of 0.001 ft and derivative given by Equation 3.

Table 1. Standard storage unit shapes

Shape		Coefficients	Dimensions
Elliptical Cylinder		$a_0 = (\pi/4)LW$ $a_1 = a_2 = 0$	L = major axis length W = minor axis width
Elliptical Paraboloid		$a_0 = a_2 = 0$ $a_1 = (\pi/4)\ LW/H$	L = major axis length W = minor axis width H = paraboloid height
Elliptical Cone		$a_0 = (\pi/4)LW$ $a_1 = \pi WZ$ $a_2 = \pi(W/L)Z^2$	L = bottom major axis length W = bottom minor axis width Z = side slope (run/rise) along major axis
Rectangular Pyramid		$a_0 = LW$ $a_1 = 2(L + W)Z$ $a_2 = 4Z^2$	L = bottom length W = bottom width Z = wall slope (run/rise) (same for each face)

3.2 Functional Storage Shapes

SWMM's functional storage shape option uses a power law to relate surface area to depth:

$$A = c_0 + c_1 Y^{c_2} \tag{5}$$

where c_0, c_1, and c_2 are user-supplied constants.

The surface area at a given depth is found directly from this equation. The relation between volume V and depth Y (required for dynamic wave analysis) is:

$$V = c_0 Y + \left(\frac{c_1}{c_2 + 1}\right) Y^{c_2+1} \tag{6}$$

To find the depth associated with a given volume (required for kinematic wave analysis) one solves the following nonlinear equation for Y:

$$f(Y) = V - \left(c_0 Y + \left(\frac{c_1}{c_2 + 1}\right) Y^{c_2+1}\right) = 0 \tag{7}$$

It is solved using the Newton-Raphson-Bisection method over the interval [0, Y_{full}] with initial estimate $Y = V/(c_0 + c_1)$, convergence tolerance of 0.001 ft and derivative $f'(Y)$ given by Equation 5.

Some shapes and their coefficients that can be represented with this functional option include:

- Shapes with vertical sides and constant surface area no matter how irregular in outline, including cylinders and rectangular prisms:
  c_0 = area of the base
  $c_1 = c_2 = 0$.

- An open channel with a trapezoidal cross-section and vertical ends:
  $c_0 = WL$
  $c_1 = 2ZL$
  $c_2 = 1$
  where W = bottom width of cross-section, L = channel length, and Z = side slope.

- An open channel with a parabolic cross-section and vertical ends:
  $c_0 = 0$
  $c_1 = WLH^{0.5}$
  $c_2 = 1$
  where W = top width, L = channel length and H = full height.

- An elliptical paraboloid:
  $c_0 = 0$
  $c_1 = A/H$
  $c_2 = 1$
  where A is the surface area at height H.

3.3 Tabular Storage Shapes

The shape of a storage unit can also be defined by a Storage Curve which is a series of user-supplied data pairs Y_i, A_i that represent the points on a curve of surface area versus depth above the bottom of the unit. An example of this type of curve is shown in Figure 2. It can represent natural depressions with irregular-shaped contour intervals, spheroid storage vessels or conventional shapes with different base sizes stacked atop one another. The first point supplied to the curve should be the surface area of the unit's base at a depth of 0. Otherwise, it will be assumed that the unit has zero surface area at its base. The curve will be extrapolated outwards to meet the unit's maximum depth if need be.

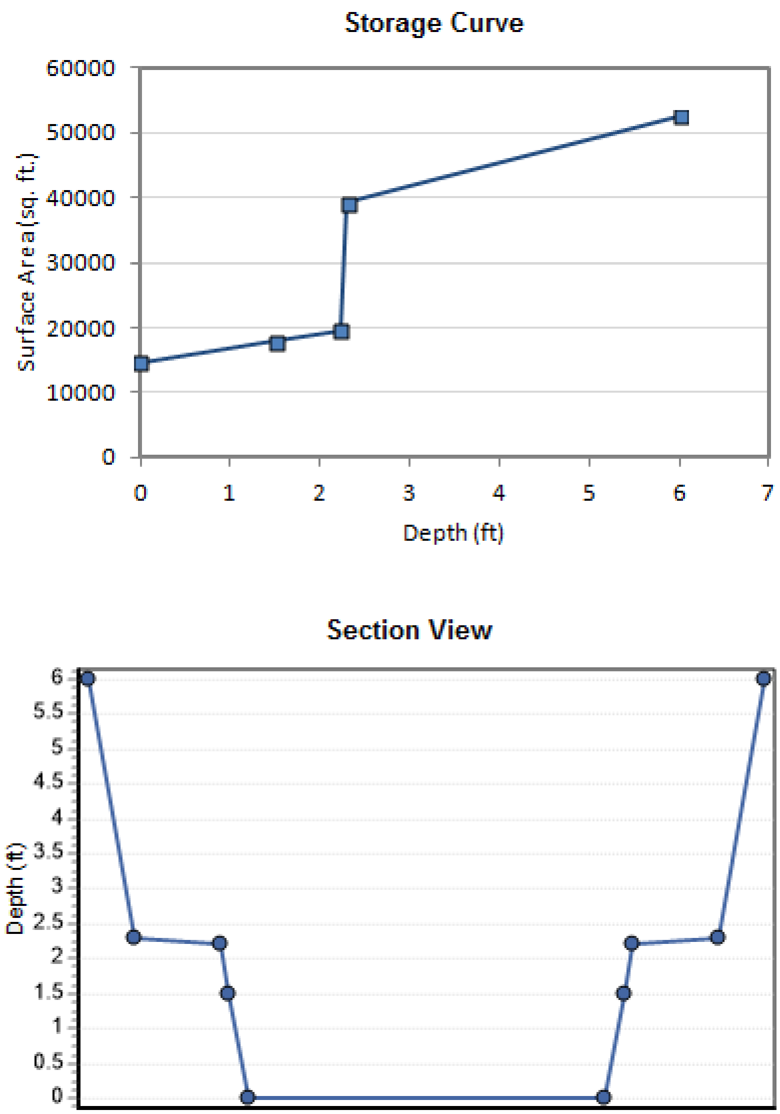


Figure 2. Example of a storage curve and its section view

To find the area associated with a given storage depth one interpolates between data points that bracket the depth value on the storage curve. Determining the storage volume V at a given depth Y is equivalent to finding the area under the storage curve from depth 0 to Y. This can be done by using the Trapezoidal Rule (Atkinson, 1989) which results in:

$$V = \frac{1}{2}\left\{\sum_{i=1}^{n}(Y_i - Y_{i-1})(A_i + A_{i-1})\right\} + \frac{1}{2}(Y - Y_n)(A + A_n) \tag{8}$$

where n is the largest data point index with $Y_n \leq Y$ and A is the surface area associated with depth Y as found from the storage curve itself. The shaded rectangles in Figure 3 illustrate how the trapezoidal rule is applied to a storage curve to find the stored volume at a particular depth. This procedure is the same as the widely used Average-End-Area method except that the area at the desired depth is first interpolated from the storage curve rather than converting the original area curve to a volume curve and interpolating directly from it.

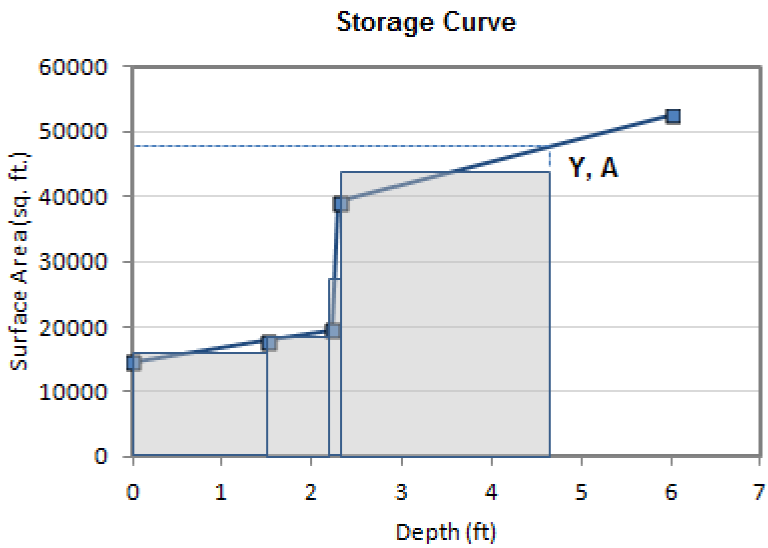


Figure 3. Finding the volume at a given depth for a storage curve

The depth that corresponds to a particular volume for a storage curve can be found as follows. Using the trapezoidal rule, sum the volumes contributed by each curve segment starting from 0 until the accumulated volume V_{sum} exceeds the target volume V. Let the data point index at the start of this segment be denoted by i. Then the depth Y that results in volume V is:

$$Y = Y_i + \left[\sqrt{A_i^2 + 2\alpha(V - V_{sum})} - A_i\right]/\alpha \qquad (9)$$

where $\alpha = (A_{i+1} - A_i)/(Y_{i+1} - Y_i)$.

4. Pumps

SWMM treats pumps as links that have a pre-defined relationship between flow rate Q and head H or some suitable surrogate. This relationship is defined by a user-supplied Pump Curve. Table 2 depicts the five types of pump curves that SWMM recognizes. Although not a requirement, a pump's inlet node would typically be a storage node that represents a pump station's wet well. An exception would be an inline booster pump placed inside a force main line under dynamic wave analysis. A sixth type of pump, called an Ideal pump, does not use a pump curve but instead has its flow rate equal to the inflow rate into its inlet node. It must be the only outflow link from its inlet node and is used mainly for conceptional design.

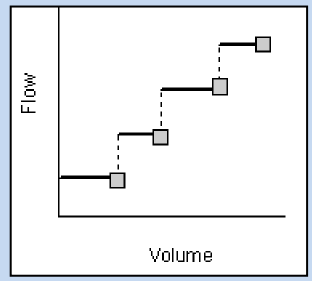
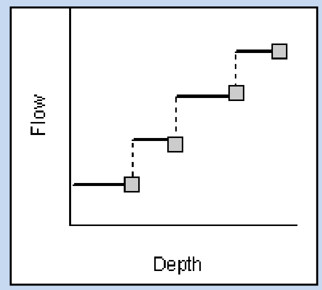
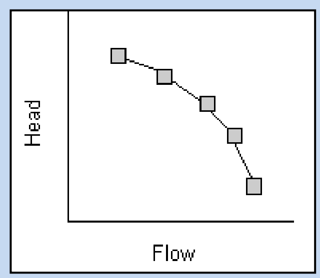
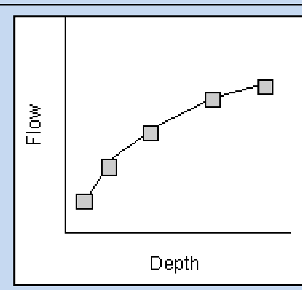
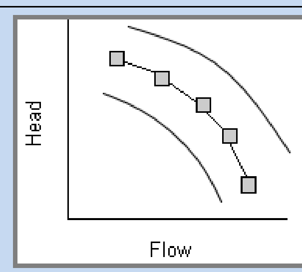
A single point on a Type1 or Type2 curve would typically represent an operating point for a constant flow positive displacement pump. Additional points might represent flow rates at different pump speeds or contributions from additional constant speed pumps running in parallel. The Type3 curve represents the characteristic curve of a centrifugal pump operating at some fixed speed, where there is a continuous range of flows available depending on the head required. The Type4 curve could be a positive displacement pump with continuous speed control or a centrifugal pump that lifts water to a more or less fixed elevation so that the required head depends only on the water level at its inlet node. A Type5 pump is a variable speed version of the Type3 pump. As the pump's impeller speed varies relative to some nominal value, flow changes in direct proportion, while head changes in proportion to the speed squared.

Whenever a pump link is encountered in either the dynamic wave or kinematic wave methods its new flow is found directly from its pump curve using previously computed values were for nodal heads and volumes.

For Type1 and Type2 curves, the curve is searched in stepwise fashion for the first point whose volume or depth exceeds the volume or depth at the pump's inlet node. The pump's flow is the flow associated with that point. For the Type3 and Type5 curves, the flow is determined by first finding the pair of adjacent data points that bracket the difference in head between the pump's outlet and inlet nodes and then interpolating a flow between these points for the given head difference. A similar lookup procedure is used for the Type4 curve except that water level at the pump's inlet node is used instead of head difference. A pump's flow is not allowed to be outside the minimum and maximum values defined by its pump curve and is not allowed to be negative.

The Type5 pump curve is shifted depending on what relative speed setting ω the pump is currently operating under, where a setting of 1.0 applies to the original user-supplied curve (i.e., the rated impeller speed). Following the pump affinity laws (Sanks et al., 1998), a point with head H and flow Q on the original curve becomes $\omega^2 H$ and ωQ, respectively, on the speed-adjusted curve. For other pump types only the flow value found from the original curve is multiplied by the speed setting.

Table 2. Pump curves recognized by SWMM

Type1 (Fixed/Volume) Consists of a series of constant flow rates that apply over a series of volume intervals at the pump's inlet node.	
Type2 (Fixed/Depth) Similar to a Type1 pump except that the fixed flow rate levels vary over a set of depth intervals at the pump's inlet node.	
Type3 (Variable/Head) Uses a pump characteristic curve at some nominal impeller speed to relate flow rate and delivered head.	
Type4 (Variable/Depth) A variable speed pump where flow varies continuously with inlet node water depth.	
Type 5 (Variable/Affinity) A variable speed version of the Type3 pump where the pump curve shifts position when control rules change the pump's relative speed setting.	

Speed settings can be changed during a simulation by using control rules. The setting can also be used to control pump operation based on wet well level (e.g., set ω to 1 when the level is above a startup depth and to 0 when below a shutoff depth). The adjusted pump flow is checked to ensure it does not cause the water level at the inlet node to drop below zero over the current time step. If the node is a storage node then the pumping rate cannot exceed Q_{max} where

$$Q_{max} = Q_{in} + V_N/\Delta t \tag{10}$$

and Q_{in} is the most recently computed total inflow to the node, V_N is the node volume at the start of the time step, and Δt is the current time step interval. If the inlet node is not a storage node and dynamic wave analysis is being made, SWMM's normal head updating formula (given in Equation 3-15a in the Hydraulics Reference Manual (Rossman 2017)) is used with the current pumping rate to estimate the inlet node head at the end of the time step. If this head is below the node's invert elevation then the pumping rate is set equal to the node's current inflow.

Some additional computational details regarding pumps are as follows:

1. If the inlet node of a Type1 (flow versus volume) pump is not a storage node then it is assigned a virtual wet well whose volume varies linearly with depth up to the highest volume on the pump curve at full node depth. While the normal non-storage node methods are used to update the node's water level, the virtual wet well volume corresponding to the node's water level is used to determine the pumping rate. Equation 10 is also used to limit the pump flow to the maximum flow that the node can release.
2. For dynamic wave modeling:
    a. Pumps do not contribute any surface area to the node-link assemblies at their inlet and outlet nodes.
    b. For Type3, Type4, and Type5 pump curves the $\partial Q/\partial H$ term used for evaluating a surcharged node, if the surcharge algorithm option is used, is the negative slope of the line segment on which the pumping rate lies. For the other pump types it is zero because their line segments have zero slope.
    c. No under-relaxation is applied to consecutive pump flows at Step 3 of the iterative solution method described in Section 3.2 of the Hydraulics Reference Manual.
3. SWMM computes the power consumed in kilowatt-hours (Kwh) by each pump over each time step Δt as:

$$Kwh = 0.7457(H_2 - H_1)\, Q(\Delta t/3600)/8.814 \tag{11}$$

where heads H_1 and H_2 are in feet, flow Q is in cfs, and time step Δt is in seconds. The pump's wire to water efficiency is not included in this calculation. The power consumption totaled up over the model simulation period and reported for each pump in SWMM's Pumping Summary Report. Also reported are the percent of time each pump is online and operates at either the lower or upper end of its pump curve.

5. Storm Drain Inlets

Storm drain inlets are structures that convey runoff from roadway pavements into below ground storm sewers (see Figure 4). Inlet type, sizing and spacing are normally chosen to meet limits on the spread and depth of water across a roadway as set by local drainage agencies to maintain public safety. The U.S. Department of Transportation Federal Highway Administration's Urban Drainage Design Manual (HEC-22) (FHWA, 2009) contains experimentally derived equations for computing the amount of flow captured by different types of inlets. These equations are widely used throughout North America and have been incorporated into SWMM's flow routing routines.

Figure 4. Examples of storm drain inlets.

Figure 5 depicts the different types of street inlet structures whose hydraulic performance is computed using the HEC-22 procedures. In addition to these standard inlet types, a custom inlet can also be deployed. Its performance is defined by a user-supplied rating curve of captured flow as a function of flow depth or a diversion curve of captured flow as a function of flow upstream of the inlet (see Figure 6). These curves are defined by a tabular listing of their data points.

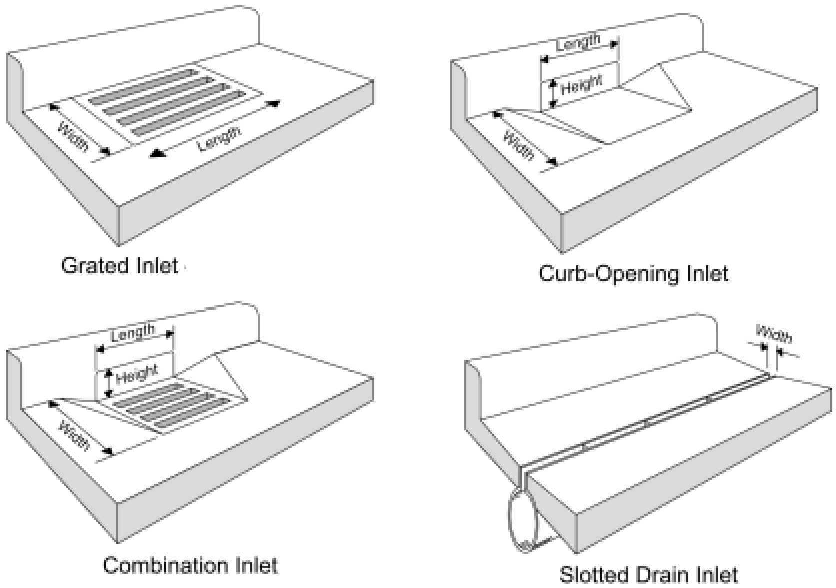


Figure 5. Standard types of curb and gutter inlets

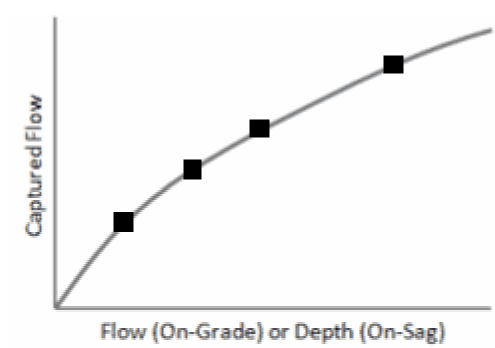


Figure 6. Performance curve for a custom inlet

5.1 Model Setup

To add storm drain inlet modeling into SWMM, a site is represented as a dual drainage system consisting of both street conduits along the ground surface and sewer conduits below ground, as shown in Figure 7. An inlet structure will divert some portion of the street flow it receives into a designated node of the sewer system with the rest being bypassed to downstream street conduits.

When an inlet's sewer node reaches its full depth any excess flow that causes it to flood is routed back into the street's downstream node rather than having it leave the system as it normally would.

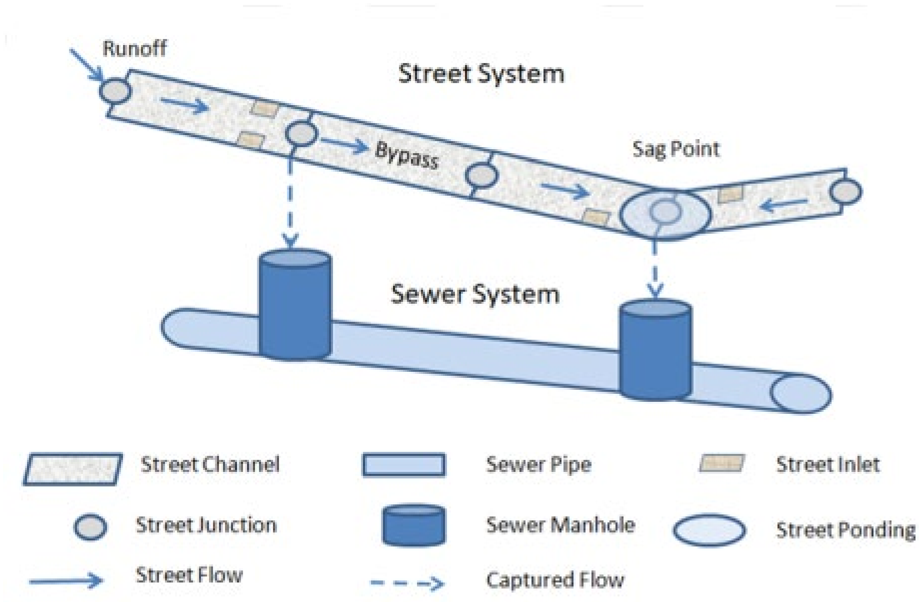


Figure 7. Representation of a dual drainage system

The HEC-22 procedures assume that the curb and gutter inlets shown in Figure 5 are placed in conduits that have a Street cross-section shape as described in Section 2 above. Even if a street conduit does not contain inlets, it should still be assigned a Street cross-section if the spread and depth of surface water across it needs to be reported. Street cross-sections can be either single-sided (i.e., have a single section that slopes downward from the street crown) or two-sided (i.e., have mirror image sloping sections on either side of the street crown) as required.

Streets can be assigned any number of a specific inlet type (e.g., grate, curb opening, combination, or slotted drain). If the cross-section is two-sided then each side receives the replicate number of inlets. If a street needs to use a mix of inlet types then it must be divided into separate street conduits where each utilizes just a single type of inlet.

As shown in Figure 7, inlets can be located either on a continuous sloping section of roadway (on-grade, sometimes referred to as a flow-by condition) or at a low point where flow tends to pool (on-sag, sometimes referred to as a sump condition). The HEC-22 procedures make flow capture for on-grade inlets a function of the approach flow rate, whereas flow capture for on-sag inlets depends on the depth of water that pools above them.

Because there is no physical link in the model, such as a shared manhole, weir, or orifice, that connects the street and sewer system to one another, there is no need to have the rim elevation of a sewer manhole match the invert elevation of the street node that sends inlet flow into it.

5.2 Computational Scheme

To account for the flow capture and diversion provided by inlets, at each flow routing time step SWMM adjusts the lateral inflows seen at the downstream nodes of street conduits with inlets and at the sewer nodes designated to receive inlet flow. These lateral flows contribute to the node flow continuity equation for dynamic wave routing and to the link flow continuity equation for kinematic wave routing. The steps involved can be summarized as follows:

1. Compute the flow captured at each street inlet using the HEC-22 procedures for standard inlets or table lookup for custom inlets, using current values of street flow rates and flow depths.
2. Add each inlet's captured flow to the lateral inflow that enters the inlet's assigned sewer node and subtract that same flow from the lateral inflow seen by the downstream node of the inlet's street conduit.
3. Add any current overflow (i.e., flooding) that an inlet's sewer node experiences onto the lateral inflow for the inlet's street node instead of having it leave the system as it normally would. This allows for a two-way flow exchange between the street and sewer once the water level in the sewer node reaches the ground elevation.
4. Apply the usual flow routing step normally taken by SWMM's routing methods.

In Step 1, because each side of a two-sided street has the same cross-section geometry and number of inlets, flow capture is computed for only one side using half the total street flow as the approach flow seen by its inlets. The one-sided flow capture is then doubled to determine the full flow capture for the entire street.

5.3 Flow Capture for On-Grade Inlets

The flow capture efficiency of an inlet placed on-grade is affected by:

- inlet type and dimensions
- approach flow rate, velocity, and spread of water on the street
- street cross-slope and curb depression
- longitudinal street slope and surface roughness.

<u>Grate Inlets</u>

For a standard street grate located on-grade the HEC-22 equation for flow capture is:

$$Q_c = Q\{R_f E_0 + R_s (1 - E_0)\} \quad (12)$$

where:

Q_c	=	captured flow (cfs)
Q	=	approach flow (cfs)
E_0	=	ratio of flow over the grate's width to total flow
R_f	=	frontal capture efficiency
R_s	=	side capture efficiency

The frontal capture efficiency R_f is:

$$R_f = 1 - 0.09\, max(0, V - V_o) \quad (13)$$

while the side capture efficiency R_s is:

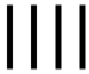
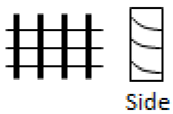
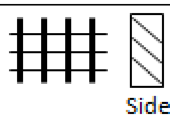
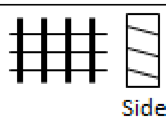
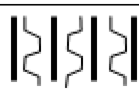
$$R_s = 1/\{1 + 0.15V^{1.8}/(S_x L^{2.3})\} \quad (14)$$

with:

V	=	velocity of flow over the grate (ft/sec)
V_0	=	velocity at which water begins to splash over the inlet (ft/sec)
S_x	=	street cross slope (ft/ft)
L	=	grate length (ft)

FHWA (2009) contains curves showing how the splash-over velocity V_0 increases with increasing grate length L for the common grate designs listed in Table 3. Table 4 contains polynomial expressions that were fit to these curves by UDFCD (2016) that are used by SWMM. For grates that do not conform to one of the listed designs, the splash-over velocity must be supplied by the user.

Table 3. Description of grate inlet types[1]

Grate Type	Layout	Description
P-50		Parallel bar grate with 1⅞” bar spacing on center
P-50x100		Parallel bar grate with 1⅞” bar spacing on center and ⅜” diameter lateral rods spaced at 4” on center
P-30		Parallel bar grate with 1⅛” bar spacing on center
Curved Vane		Curved vane grate with 3¼” longitudinal bar and 4¼” transverse bar spacing on center
45° Tilt Bar		45° tilt-bar grate with 3¼” longitudinal bar and 4” transverse bar spacing on center
30° Tilt Bar		30° tilt-bar grate with 3¼” longitudinal bar and 4” transverse bar spacing on center
Reticuline		Honeycomb pattern of lateral bars and longitudinal bearing bars

[1]See FHWA (2009) for more detailed descriptions and pictures.

Table 4. Splash-over velocity for different types of grate inlets[1]

Grate Type	Splash over velocity V_0 (ft/s) as a function of grate length L (ft)
P-50	$V_0 = 2.22 + 4.03L - 0.65L^2 + 0.06L^3$
P-50x100	$V_0 = 0.74 + 2.44L - 0.27L^2 + 0.02L^3$
P-30	$V_0 = 1.76 + 3.12L - 0.45L^2 + 0.03L^3$
Curved Vane	$V_0 = 0.30 + 4.85L - 1.31L^2 + 0.15L^3$
45° Tilt Bar	$V_0 = 0.99 + 2.64L - 0.36L^2 + 0.03L^3$
30° Tilt Bar	$V_0 = 0.51 + 2.34L - 0.20L^2 + 0.01L^3$
Reticuline	$V_0 = 0.28 + 2.28L - 0.18L^2 + 0.01L^3$

[1] Source: UDFCD (2016).

Curb Opening Inlets

For a curb opening inlet located on-grade, the HEC-22 equation for flow capture is:

$$Q_c = Q\{1 - (1 - \min(1, L/L_T))^{1.8}\} \tag{15}$$

L is now the length of the curb opening and L_T is the length at which complete flow capture occurs. The latter quantity is computed as:

$$L_T = 0.6Q^{0.42}S_L^{0.3}(nS_e)^{-0.6} \tag{16}$$

where:

S_L	=	longitudinal street slope (ft/ft)
n	=	Manning's roughness coefficient for the street surface
S_e	=	$S_x + (a/W)E_0$
a	=	curb depression (ft)
W	=	depressed gutter width (ft)
E_0	=	ratio of flow over depressed gutter width to total flow

If $L > L_T$ then complete capture is obtained.

Computing E_0

The on-grade flow capture formulas for grate and curb opening inlets requires specification of E_o, the fraction of total street flow Q within a distance W from the curb or as depicted in Figure 8, the ratio of Q_W to Q. For grates this distance is the width of the grate. For curb openings it is the width of the depressed gutter (if present).

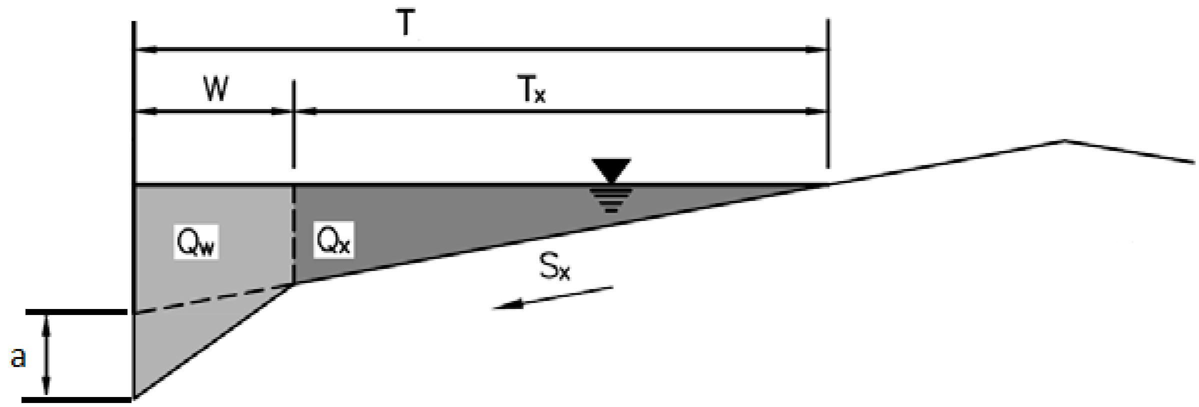


Figure 8. Street cross-section divided into gutter and roadway flow

HEC-22 bases its determination of E_0 on Izzard's form of the Manning equation that relates flow spread T to flow rate Q for a triangular cross-section. It is derived from the standard Manning equation by integrating the hydraulic radius across successive increments of street width. The result for US standard units is:

$$Q = (0.56/n)S_x^{1.67}S_L^{0.5}T^{2.67} \quad (17)$$

(Note: the standard Manning equation has the same form except with the constant being 0.47.)

Solving for T as a function of Q gives:

$$T = \left[\frac{Qn}{0.56S_x^{1.67}S_L^{0.5}}\right]^{0.375} \quad (18)$$

If the street has a uniform cross slope ($a = 0$ in Figure 8) then Equation 18 can be used to derive the following expression for E_0:

$$E_0 = 1 - (1 - W/T)^{2.67} \quad (19)$$

where T is evaluated at a given flow rate Q.

For a compound street cross-section with depressed curb ($a > 0$ in Figure 8), HEC-22 provides the following equation for E_0:

$$E_0 = \frac{1}{1 + \frac{S_W/S_X}{\left[1 + \frac{S_W/S_X}{(T/W - 1)}\right]^{2.67} - 1}} \quad (20)$$

where $S_W = S_X + a/W$. It is not possible to solve directly for E_0 because Equation 18 for $T(Q)$ applies only to a triangular section of uniform slope.

To solve Equation 20 let Q_X and T_X denote the flow and spread, respectively, across the non-depressed triangular portion of the street's cross-section. Then the following relations apply:

$$Q_X = Q(1 - E_0) \quad (21)$$

$$T_X = T - W \quad (22)$$

$$T/W - 1 = T_X/W \quad (23)$$

These can be used in the following iterative procedure to find E_0 for a particular flow rate Q:

1. Assume a value for T_X.
2. Use Equation 20 to compute E_0, with T_X/W substituted for $T/W - 1$.
3. Compute Q_X from Equation 21.
4. Compute a new value for T_X using Equation 18 with Q_X as the flow rate.
5. If there is negligible change in T_X then stop with the last value of E_0 as the solution. Otherwise return to Step 2.

In cases where the width of the grate is smaller than the width W of the depressed gutter section, E_0 is adjusted by the ratio of the flow area over the grate's width to the flow area over the depressed gutter width.

Combination Inlets

A combination inlet consists of both a grate and curb opening placed together at the same location. Its on-grade flow capture equals that of the grate plus any flow captured by the portion of the curb opening that extends upstream of the grate's length. The latter flow capture is computed first and is subtracted from the approach flow used to determine the grate's flow capture.

Slotted Inlets

The flow capture capability of a slotted inlet located on-grade is the same as that of a curb opening inlet of equal length.

Custom Inlets

If an on-grade custom inlet is supplied with a flow diversion curve (captured flow versus approach flow) then that curve will be used to determine its flow capture. If it uses a flow rating curve (captured flow versus water depth) then that curve will be used in conjunction with the water surface depth at the downstream end of the conduit containing the inlet.

5.4 *Flow Capture for On-Sag Inlets*

HEC-22 has flow capture efficiency for an inlet in a sag location depend on the size of the inlet's opening and the depth of water that collects ponds on top of it at the street curb. At low flow depths the inlet acts as a weir with

$$Q_c = C_W L_W d^{1.5} \tag{24}$$

while at higher depths it acts as an orifice with

$$Q_c = C_O A_O \sqrt{2gd} \tag{25}$$

In these equations:

C_W = weir coefficient ($ft^{0.5}$/sec)
C_O = orifice coefficient
g = acceleration due to gravity (ft/sec^2)
L_W = effective length of inlet (ft)
A_O = open area of inlet (ft^2)
d = effective depth of water at the inlet (ft).

Grate Inlets

For grate inlets the following values are used in Equations 24 and 25:

C_W = 3.0
C_O = 0.67
L_W = $L + 2W$
A_O = LWf_O

$$d \quad = \quad d_i - (W/2)S_W$$

where L is the grate's length, W its width, f_O the ratio of open area to full area, and d_i is the depth of water at the downstream node of the conduit containing the inlet. Opening area ratios for several types of grate designs are listed in Table 5.

HEC-22 does not provide clear guidance on what depth causes a switch from weir flow to orifice flow for grates. Therefore, it is assumed the switch occurs at a depth d where Equation 24 equals Equation 25. This results in weir flow for depths below $1.79\, A_O/L_W$ and orifice flow for depths above it.

Table 5. Open area relative to full area for grate inlets[1]

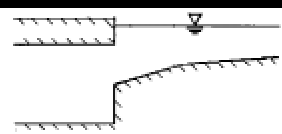
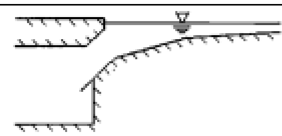
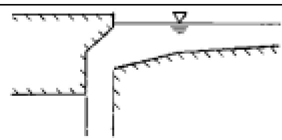
Grate Type	Open Area Ratio
P-50	0.90
P-50x100	0.80
P-30	0.60
Curved Vane	0.35
45° Tilt Bar	0.17 (assumed)
30° Tilt Bar	0.34
Reticuline	0.80

[1]Source: Chart 9B of FHWA (2009)

Curb Opening Inlets

For streets with uniform cross slope or for openings greater than 12 feet in length, the values used in Equation 24 for weir flow are C_W= 3.0 and L_W= opening length. Otherwise, C_W= 2.3 and $L_W = L + 1.8W$ where L = opening length and W = width of the depressed gutter. The values used in Equation 25 for orifice flow are $C_O = 0.67$ and $A_O = hL$ where h is the height of the opening. The effective depth d occuring at the curb opening inlet under orifice flow depends on the orientation of the opening's throat relative to the street surface as shown in Table 6.

Table 6. Effective depth for curb opening inlets under orifice flow

Throat Angle		Effective Depth
Horizontal		$d = d_i - h/2$
Inclined		$d = d_i - 0.7071(h/2)$
Vertical		$d = d_i$

HEC-22 states that weir flow for on-sag curb openings occurs at effective depths below h while orifice flow occurs at depths greater than $1.4h$. For depths in between these SWMM uses the following interpolation formula:

$$Q_c = (1 - r)Q_{weir} + rQ_{orif} \qquad (26)$$

where Q_{weir} is weir flow capture at depth h, Q_{orif} is orifice flow capture at depth $1.4h$ and $r = (d - h)/(0.4h)$.

Slotted Inlets

For slotted inlets the variables in the weir and orifice Equations 24 and 25 are as follows:

C_W = 2.48
C_O = 0.8
L_W = L
A_O = LW
d_i = d

where L = inlet length and W = inlet width. Weir flow holds for $d \leq 0.2$ feet while orifice flow occurs for $d \geq 0.4$ feet. In between these values flow capture is computed using Equation 26 with Q_{weir} as weir flow capture at depth 0.2, Q_{orif} as orifice flow capture at depth 0.4 and $r = (d - 0.2)/0.2$.

Custom Inlets

If an on-sag custom inlet is supplied with a flow rating curve (captured flow versus water depth), then that curve is used to determine its flow capture. The depth supplied to the curve's lookup table is the depth of the downstream node of the conduit containing the inlet. If the inlet was assigned a diversion curve (captured flow versus approach flow) then that curve is used, thus essentially treating the inlet as if it were on-grade.

5.5 Drop Inlets

Drop inlets, pictured in Figure 9, are used to drain water from roadside ditches, swales, and flat bottom channels. SWMM allows these structures to be placed in open channels that have either an open rectangular or trapezoidal cross-section. Model set-up for utilizing these inlets is the same as described in Section 5.1 above and the same computational scheme applies. The methods used to compute their flow capture efficiencies are described in the following paragraphs.

Figure 9. Types of channel drop inlets

Drop Grate Inlets

The flow capture equation for a drop grate inlet located on-grade is the same as for a street grate (see Equation 12) except that the ratio E_0 of flow over the grate to total cross-section flow Q is given by:

$$E_0 = \frac{1.486\sqrt{S_L}(yW)^{1.67}}{nQ(W + 2y)^{0.67}} \tag{27}$$

where:

W	=	side length of grate parallel to flow direction (ft)
y	=	flow depth in the channel (ft)
n	=	channel Manning's roughness coefficient
S_L	=	channel longitudinal slope (ft/ft)

A cross-slope S_X of 1% is assumed unless the grate extends across the entire bottom width of a trapezoidal channel. In that case S_X is taken as the slope of the channel's side wall.

Drop grates located on-sag use the same weir and orifice equations (24 and 25) as do street grates with the only difference being that for weir flow the effective length of the inlet's sides (L_W in Equation 24) is the sum of the lengths of all four sides.

<u>Drop Curb Inlets</u>

Flow capture for drop curb inlets is computed the same as for curb opening inlets located on sag. The only difference is that the effective length of the opening is the total length of all four sides and the open area is the height of the opening times the total length of all four sides.

6. References

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