

**H y d r o C A D**®  
*Stormwater Modeling System*  
Version 8  
**Owner's Manual**

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## Section 18 - Reach Routing Calculations

A reach is used to perform an *independent hydrograph routing* through an open channel, or through a pipe flowing under open-channel conditions. A channel or pipe can alternatively be modeled as a flow segment within a subcatchment, where its travel time will contribute to the Tc. The latter approach is usually simpler, and may even be necessary in the case of a subcatchment that is draining along the entire length of the reach. However, for a long reach with a significant inflow at one end, a separate reach routing may be called for. This section details the procedures used to perform an independent reach routing.

### The Routing Curves

Reach routing requires that the reach first be characterized by two curves: the end-area vs. depth (stage-storage), and the discharge vs. depth (stage-discharge). This information may be determined by one of the following procedures:

- 1) The user may directly specify the end-area and *discharge* at any number of depths. Values for intermediate depths are interpolated as described on page 70.
- 2) The user may enter the end-area and *wetted perimeter* at each depth. Values for intermediate depths are interpolated as described on page 70. Manning's equation is then used to calculate the discharge at each depth (see [Basic Hydraulics p.77](#)):

$$V = \frac{1.486 R^{\frac{2}{3}} S_0^{\frac{1}{2}}}{n} \quad \text{Eq. 19}$$

V=Average velocity of flow [ft/sec] or [m/sec]  
1.486=English factor (use 1.0 for metric)  
R=Hydraulic radius [ft] or [m]  
S<sub>0</sub>=Slope of hydraulic grade line [rise/run]  
=Slope of channel bottom, assuming normal flow  
n=Manning's number (See table on page 144)

$$\text{also } R = \frac{A}{P} \quad \text{and} \quad Q = VA \quad \text{Eq. 20}$$

A=Area of flow [ft<sup>2</sup>] or [m<sup>2</sup>]  
P=Wetted perimeter [ft] or [m]  
Q=Flow [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]

$$\text{thus } Q = \frac{1.486 \left(\frac{A}{P}\right)^{\frac{2}{3}} S_0^{\frac{1}{2}} A}{n} = 1.486 \frac{A^{\frac{5}{3}} S_0^{\frac{1}{2}}}{n P^{\frac{2}{3}}} \quad \text{Eq. 21}$$

- 3) For a rectangular, vee, trapezoidal, parabolic, or circular (pipe) channel, the user may provide the appropriate dimensions, and HydroCAD will determine the end-area and discharge curves using the cross section equations on page 154, and Manning's equation as shown above.

4) Other shapes, such as natural channels, can be described by entering a custom cross-section. The section is defined by a table of coordinates that indicate the offset and elevation of points along the cross-section. Manning's equation is then used to calculate the flow at any required depth.

5) A custom cross-section may also be defined in which each segment has a different Manning's value. The total flow is determined with a *composite* Manning's value or segmented flow, using one of the following methods. (See [Open Channel Hydraulics](#) p.136.)

Horton (deep flow) method

$$n_c = \left[ \frac{\sum (n_i^{3/2} P_i)}{\sum P_i} \right]^{2/3} \quad \text{Eq. 22}$$

$n_c$ =Composite Manning's number  
 $n_i$ =Manning's value for segment i  
 $P_i$ =Wetted perimeter for segment i

This technique is commonly used for “deep” channels, where the velocity is relatively constant throughout the cross-section. If applied to a section with a constant Manning's value, the result is identical to the original Manning's value.

Pavlovskii (shallow flow) method

$$n_c = \left[ \frac{\sum (n_i^2 P_i)}{\sum P_i} \right]^{1/2} \quad \text{Eq. 23}$$

$n_c$ =Composite Manning's number  
 $n_i$ =Manning's value for segment i  
 $P_i$ =Wetted perimeter for segment i

This technique is commonly used for “shallow” channels, where the velocity may vary considerably between segments. It is based on the assumption that the total resistant force for the cross-section is the sum of the resistant force for each of the segments.

Lotter (subdivided flow) method

$$n_c = \frac{P R^{5/3}}{\sum \left( \frac{P_i R_i^{5/3}}{n_i} \right)} \quad \text{Eq. 24}$$

$n_c$ =Composite Manning's number  
 $n_i$ =Manning's value for segment i  
 $P_i$ =Wetted perimeter for segment i  
 $R_i$ =Hydraulics radius for segment i = Area<sub>i</sub>/P<sub>i</sub>  
 $P$ =Total wetted perimeter = sum(P<sub>i</sub>)  
 $R$ =Hydraulic radius for entire channel = Area/P

This technique is based on the assumption that the total flow is equal to the sum of the flows for the individual segments. If applied to a section with a constant Manning's value, the result is *not* the same as the original Manning's value.

#### Subdivision by Segment

$$Q = \sum Q_i \quad \text{Eq. 25}$$

Q=Total flow for cross-section [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]  
Q<sub>i</sub>=Flow for segment i (see eq.21) [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]

This technique produces exactly the same flow as the Lotter method, described above. It differs only in the calculation procedure, in which the total flow is the sum of the flows calculated separately for each segment, without the use of a composite Manning's value.

#### Subdivision by Manning's Value

$$Q = \sum Q_n \quad \text{Eq. 26}$$

Q=Total flow for cross-section [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]  
Q<sub>n</sub>=Flow for consecutive segments with same Manning's value

This technique subdivides the channel only when there is a change (break) in the Manning's value. This produces more consistent results than subdivision by segment, in that the resulting flow is independent of the number of points along the cross section. When all segments have the same Manning's value, the flow is identical to the traditional solution for a constant Manning's value. This technique is similar (although not identical) to the current procedure used in HEC-RAS.

#### Other Procedures

If another technique is used to calculate flow through a complex cross-section, the rating curve can be calculated separately and entered into HydroCAD using option 1, above. However, using a defined geometry or cross-section allows direct evaluation of the channel at any depth, without having to interpolate between a (smaller) number of user-defined stages.

### **Reach Routing Limitations**

The preceding stage-discharge calculations are based solely on Manning's equation, and do *not* consider possible inlet, outlet, or tailwater effects. If a complete analysis is desired for a pipe, including entrance losses and possible tailwater effects, it should be modeled as a pond with a culvert outlet. If a detailed water surface profile is required for a channel, you should use a program specifically designed for that purpose.<sup>23</sup>

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<sup>23</sup> Surface water profiles are usually calculated under constant-flow conditions, rather than with a hydrograph (time-varying flow). Peak flows (from HydroCAD or another hydrograph model) are often used as input for these calculations.

## Reach Routing Table

When performing a reach routing, HydroCAD uses an internal routing table to provide storage and discharge information at any required depth. The construction of this table depends on the selected reach type, as listed on page 67. When entering discharge or wetted-perimeter directly (reach types 1 or 2), several **interpolation options** are available:

**Linear:** This option creates a routing table containing the same number of depth values (stages) specified by the user. When the routing is performed, intermediate storage and discharge values are obtained by linear interpolation between these stages. (This option is provided primarily for compatibility with HydroCAD 7.1 and earlier.)

**Multi-point:** This option creates a routing table with a larger number of evenly-spaced depth intervals (normally 100). Each user-specified depth is also included in the table, to ensure accuracy at these exact depths. Storage is calculated at each tabulated depth using a linear interpolation between user-defined stages. When entering wetted-perimeter, linear interpolation is used to determine the perimeter at each tabulated depth, and the corresponding discharge is calculated with Manning's equation. When entering discharge, linear interpolation is used to determine the discharge at each tabulated depth. Multi-point is the default option, and is recommended for most situations.

**Parabolic:** This option creates a routing table with a larger number of evenly-spaced depths, just like Multi-point, except that intermediate values are determined by parabolic interpolation using the *three* adjacent user-defined stages. This option may provide greater accuracy when the user-supplied rating table contains a limited number of stages. However, the resulting storage and discharge plots should be examined to be sure that a parabolic fit is appropriate for the data.

Note: Due to ongoing software development, other interpolation options may be available in the latest software release.

When using a standard channel geometry or cross-section (reach types 3 to 5, starting on page 67), the routing table normally contains 100 evenly-spaced depth values, ranging from zero depth up to the overall depth of the reach. At each tabulated depth, HydroCAD calculates the perimeter, storage, and discharge based on the channel geometry and Manning's equation.

For all reach types, the finished routing table is used to perform the actual routing calculations, using a linear interpolation to determine the storage and discharge at intermediate depths. If greater accuracy is required, the number of depth increments can be increased on the Advanced tab of the applicable reach.

## Reach Routing Methods

HydroCAD currently provides the following techniques for reach routing, as described in the remainder of this section.

- Storage-Indication Method (Stor-Ind)
- Storage-Indication plus Translation (Stor-Ind+Trans)
- Dynamic Storage-Indication Method (Dyn-Stor-Ind)
- Muskingum-Cunge Method
- Dynamic Muskingum-Cunge Method
- Simultaneous Routing (Sim-Route)

## Storage-Indication Method

The Storage-Indication method (Stor-Ind) is the most basic reach routing technique provided by HydroCAD, and is based on the routing equations developed on page 103. The actual routing procedure is as follows.

- 1) The reach's **stage-discharge** relationship is calculated as described above.
- 2) The **stage-storage** relationship is determined from the reach cross-section multiplied by the length.
- 3) The stage-discharge and stage-storage curves are used to create a **storage-indication** curve.
- 4) Routing is performed using the specified time span and time increment. At each point in time, a storage-indication value is calculated based on the current inflow, plus the previous inflow, outflow, and volume in the reach.
- 5) The current storage-indication value and the storage-indication curve are used to determine the new elevation.
- 6) Using the new elevation, the stage-storage and stage-discharge curves are consulted to determine the new storage and discharge.
- 7) This process is repeated for all points in the inflow hydrograph.

In practice, the procedure may incorporate a number of other factors, such as a base flow or inflow loss. Any unusual conditions, such as the channel overtopping, will produce a specific warning message as listed on page 115.

## Storage-Indication plus Translation

The Stor-Ind+Trans method is identical to the Storage-Indication method described above, except that the storage-routed hydrograph is subject to a further time lag (translation) by the travel time, as defined on page 113. This is an early technique provided by HydroCAD to allow for travel time on some reaches. For longer reaches, or when peak timing is critical, a full kinematic routing procedure is recommended, such as the Muskingum-Cunge method, described below.

## Dynamic Storage-Indication Method

The Dyn-Stor-Ind reach routing procedure is identical to the Storage-Indication method described above, except that the calculations are performed over the entire watershed at each time step. Although the reach routing results are unchanged, this allows the overall watershed to be analyzed in a dynamic manner so that *ponds* may respond to tailwater effects as described on page 105.

## Muskingum-Cunge Method

This routing method is intended to duplicate results that would be obtained with the current Win-TR-20 software. (See Muskingum-Cunge Flood Routing Procedure in NRCS Hydrologic Models by William H. Merkel.) The basic HydroCAD procedure is as follows:<sup>24</sup>

### Step 1: Determine m-value vs. Depth

The m value defines the relationship between the flow velocity (V) and the wave velocity or celerity (c). m is the slope of the discharge-area curve in a log-log plot, and is constant at all depths for basic channel geometries, such as vee and trapezoidal. However, for complex cross sections, and especially for flood plains, the value can vary considerably with depth. To handle these situations, HydroCAD uses a weighted m value, according to the same procedure developed for TR-20.

When stage data is entered directly, the m value is calculated at each user-specified depth, and then interpolated to the depths used in the internal routing table. When using a standard channel geometry or cross-section, m is directly calculated at each depth in the routing table.

### Step 2: Select Reference Flow

HydroCAD currently provides a constant-parameter implementation of the Muskingum-Cunge procedure. This requires the selection of a constant reference flow at which the routing parameters will be determined. When using a sequential routing procedure, the reference flow is set equal to the peak inflow. When using a dynamic routing procedure, the peak is unknown until the completion of the routing, so the reference flow is set equal to the channel-full capacity. In either case, the user may override the default value by entering the preferred reference flow on the reach edit screen.

### Step 3: Determine Wave Velocity

Using the reference flow, the equivalent flow depth, velocity, and m value are determined by linear interpolation from the routing table. (The user may override the automatic m value by entering the preferred value on the reach edit screen.) The wave velocity (celerity) is then given by:

$$c = m V \quad \text{Eq. 27}$$

c=Wave velocity (celerity) [ft/sec] or [m/sec]  
m=Rating curve exponent  
V=Flow velocity [ft/sec] or [m/sec]

### Step 4: Determine Time and Distance Steps

The time step ( $\Delta t$ ) is generally selected in order to provide sufficient definition for the runoff and inflow hydrographs. This selection will generally ensure that the inflow peak occurs after at least ten time steps, as recommended in the TR-20 implementation. If necessary, a smaller time step can be specified.

The overall reach length may require division into a number of equal sub-reaches of length  $\Delta x$ , such that  $\Delta x$  is approximately equal to the distance traveled by the flood wave in a single time step:

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<sup>24</sup> Due to ongoing software development, the details of this implementation are subject to change over time. For the latest updates, as well as additional details, please visit the Support Page at [www.hydrocad.net](http://www.hydrocad.net)

to obtain  $\Delta x \approx c \Delta t$  where  $\Delta x = \frac{L}{N}$

$$\therefore N = \text{round} \left( \frac{L}{c \Delta t} \right)$$

Eq. 28

$\Delta x$ =Distance step (length of sub-reach) [ft] or [m]

$\Delta t$ =Time step (dt) [sec]

$c$ =Wave velocity (celerity) [ft/sec] or [m/sec]

$L$ =Total reach length [ft] or [m]

$N$ =Number of sub-reaches

Note that  $N$  is rounded to the nearest whole number, but never less than 1.

### Step 5: Determine Routing Parameters

The following equation defines the Muskingum relationship between reach inflow, outflow, and storage:

$$S = K[XI + (1-X)O]$$

Eq. 29

$S$ =Reach storage [ft<sup>3</sup>] or [m<sup>3</sup>]

$K$ =Storage constant [sec]

$X$ =Weighting factor [dimensionless]

$I$ =Reach inflow [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]

$O$ =Reach outflow [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]

The routing parameters  $K$  and  $X$  are given by:

$$K = \frac{\Delta x}{c}$$

Eq. 30

$K$ =Wave travel time through sub-reach [sec]

$\Delta x$ =Distance step (length of sub-reach) [ft] or [m]

$c$ =Wave velocity (celerity) [ft/sec] or [m/sec]

$$X = \frac{1}{2} \left( 1 - \frac{Q}{B S_o c \Delta x} \right) = \frac{1}{2} \left( 1 - \frac{VD}{S_o c \Delta x} \right)$$

Eq. 31

$X$ =Routing factor (0.0 to 0.5)

$Q$ =Reference flow [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]

$B$ =Average flow width of reference flow [ft] or [m]

$V$ =Reference flow velocity [ft/sec] or [m/sec]

$D$ =Reference flow depth [ft] or [m]

$S_o$ =Slope of hydraulic grade line [rise/run]

=Slope of channel bottom, assuming normal flow

Note that the selection of  $\Delta x$  will produce a wave travel time  $K$  that approximates the time step  $\Delta t$ . The routing factor  $X$  controls the peak outflow, with smaller values producing more attenuation.

## Step 6: Calculate Routing Coefficients

Conservation of mass is assured by use of the continuity equation:

$$S_2 - S_1 = \left[ \frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2} \right] \Delta t \quad \text{Eq. 32}$$

$S_1, S_2$  = Storage at time  $t_1$  and  $t_2$  [ft<sup>3</sup>] or [m<sup>3</sup>]  
 $I_1, I_2$  = Inflow at time  $t_1$  and  $t_2$  [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]  
 $O_1, O_2$  = Outflow at time  $t_1$  and  $t_2$  [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]  
 $\Delta t$  = Time difference between  $t_1$  and  $t_2$  [sec]

Combining with eq.29 and simplifying yields the final routing equation:

$$O_2 = C_1 I_1 + C_2 I_2 + C_3 O_1$$

where  $C_1 = \frac{\Delta t/K + 2X}{C_0}$        $C_2 = \frac{\Delta t/K - 2X}{C_0}$       Eq. 33

$$C_3 = \frac{2(1-X) - \Delta t/K}{C_0}$$
$$C_0 = \frac{\Delta t}{K} + 2(1-X)$$

## Step 7: Perform Hydrograph Routing

The routing equation (eq. 33) is applied at each time step  $\Delta t$  in the inflow hydrograph. If the reach has been divided into sub-reaches ( $N > 1$ ), the calculation is repeated for each sub-reach, using the outflow of the previous sub-reach as the inflow to its successor.

The continuity equation (eq. 32) is also evaluated at each time step in order to determine the reach storage, average depth, and average flow velocity over the length of the reach.

As an aid to evaluating the routing results, a detailed list of routing parameters is included in the reach summary report. (Click any part of the report for a detailed discussion of each parameter.)

### Dynamic Muskingum-Cunge Method

The Dynamic Muskingum-Cunge procedure is identical to the standard Muskingum-Cunge procedure described above, except that the calculations are performed over the entire watershed at each time step. Although the reach routing results are unchanged, this allows the overall watershed to be analyzed in a dynamic manner so that *ponds* may respond to tailwater effects as described on page 105.

The Dynamic Muskingum-Cunge procedure will produce the same reach routing results as the standard (sequential) Muskingum-Cunge procedure, as long as the same reference flow is used.

## Simultaneous Reach Routing

The Sim-Route reach routing procedure is provided for compatibility with simultaneous pond routing. Although this method does *not* currently allow reaches to respond to tailwater changes, it does allow the overall watershed to be analyzed in a simultaneous manner so that *ponds* may respond to tailwater effects as described on page 107.

Simultaneous reach routing is based on the basic equation for conservation of mass. (See Hydrologic Analysis and Design p.545.)

$$I - O = \frac{\Delta S}{\Delta t} \quad \text{where} \quad \Delta S = S_2 - S_1$$

Eq. 34

$$\therefore S_2 = S_1 + (I - O)\Delta t$$

I=Inflow rate [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]  
O=Outflow rate [ft<sup>3</sup>/sec] or [m<sup>3</sup>/sec]  
 $\Delta t$ =Time increment (dt) [sec]  
 $\Delta S$ =Change in storage [ft<sup>3</sup>] or [m<sup>3</sup>]  
 $S_1$ =Storage at start of time interval [ft<sup>3</sup>] or [m<sup>3</sup>]  
 $S_2$ =Storage at end of time interval [ft<sup>3</sup>] or [m<sup>3</sup>]

The following procedure is used to perform the actual hydrograph routing:

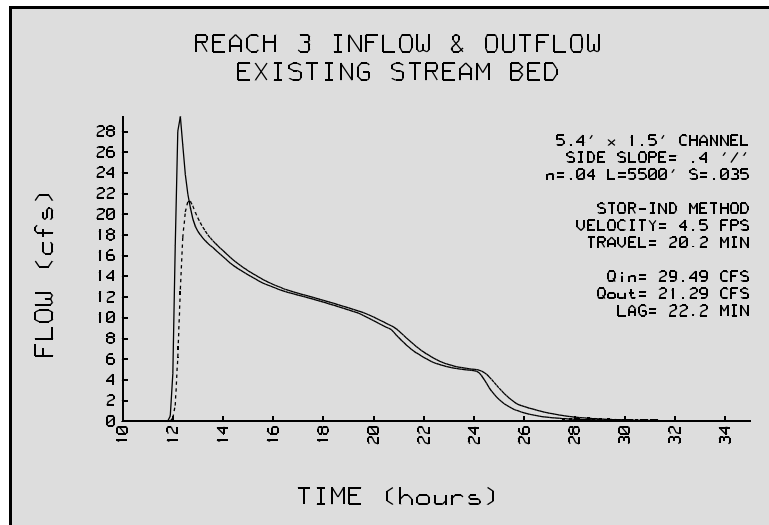
- 1) Routing is performed using the specified time span and time increment, and begins with no water stored in the reach.
- 2) The new reach storage ( $S_2$ ) is calculated using the above equation with the previous rates of inflow and outflow. (Using the previous value allows non-sequential flows, for which the current inflow is unknown.)
- 3) Using the new storage volume, a new flow depth is calculated based on the assumption of normal flow.
- 4) Using the new flow depth, a new discharge is calculated from Manning's equation or from the user-defined stage-discharge relationship.
- 5) Steps 2 through 4 are repeated at each time interval until the entire hydrograph has been developed.

Additional considerations apply to all simultaneous routing procedures as described on page 107.

## Effects of Reach Routing

A reach will normally *attenuate and delay* the hydrograph that is routed through it. The extent of this transformation depends on many factors, including the reach dimensions, slope, and Manning's number. Short reaches (up to several hundred feet) often have a minimal effect on the routed hydrograph. For this reason they are frequently modeled as a flow segment within a subcatchment.

On the other hand, for long reaches with large cross-sections, low slopes and/or high Manning's numbers, the routing effect can be significant. The graph at right shows the effects of storage-indication routing through a 5500 foot long channel. Significant attenuation may also occur on shorter reaches if the inflow peak is of short duration.



## Allowing for Travel Time

The storage-indication method, as illustrated above, accounts for only the storage effects of the reach. Other techniques must be used to account for the kinematic effects of long reaches, such as the “Stor-Ind+Trans” method described on page 71. A close examination of the graph below reveals that the peak discharge no longer corresponds to a point on the inflow curve, but is translated according to the travel time.

A better option for modeling kinematic effects is the Muskingum-Cunge method described on page 72. This is the standard reach routing procedure in the latest Win-TR-20 release, and is recommended when significant kinematic effects are present.

