Channel Routing

Basic Equations Unsteady, free surface flow in channels is also represented by the kinematic approximation to the equations of unsteady, gradually varied flow. Channel segments may receive uniformly distributed but time-varying lateral inflow from overland flow elements on either or both sides of the channel, from one or two channels at the upstream boundary, or from an area at the upstream boundary. The dimensions of overland flow units are chosen to completely cover the watershed, so rainfall on the channel is not considered directly. The continuity equation for a channel with lateral inflow is

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_c(x,t) \tag{1}$$

where A is the cross-sectional area, Q is the channel discharge, and $q_c(x,t)$ is the net lateral inflow per unit length of channel. Under the kinematic assumption, Q can be expressed as a unique function of A and equation (1) can be rewritten as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial A}\frac{\partial A}{\partial x} = q_c(x,t) \tag{2}$$

The kinematic assumption is embodied in the relationship between channel discharge and cross-sectional area such that

$$Q = \alpha R^{m-1} A \tag{3}$$

where R is the hydraulic radius. If the Chezy relationship is used, $\alpha = CS^{1/2}$ and $m = 3/2$. If the Manning equation is used, $\alpha = 1.49\, S^{1/2}/n$ and $m = 5/3$. Channel cross sections may be approximated as trapezoidal or circular, as shown in Figure 1.

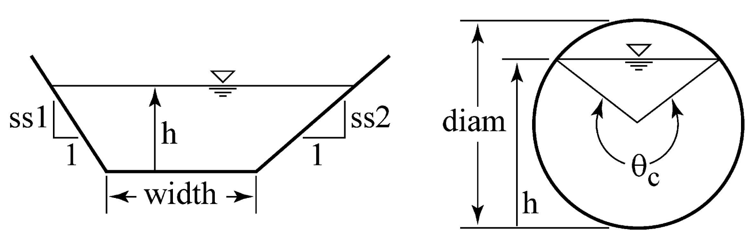

Figure 1. Definition sketch for a trapezoidal channel (left) and a circular conduit (right).

Circular Conduits In an urban environment, circular conduits must be used to represent storm sewers. To apply the kinematic model, there must be no backwater, and the conduit is assumed to maintain free surface flow conditions at all times - there can be no pressurization. The continuity equation for a circular conduit is the same as equation (2) with $q_c = 0$. That is, there is no lateral inflow. The upper boundary condition is a specified discharge as a function of time. The most general discharge relationship and the one often used for flow in pipes is the Darcy-Weisbach formula,

$$S_f = \frac{f_D}{4R}\frac{u^2}{2g} \tag{4}$$

where S_f is the friction slope, f_D is the Darcy-Weisbach friction factor, and u is the velocity (Q/A). Under the kinematic assumption, the conduit slope S may be substituted for S_f in equation (4), so that

$$u = 2\sqrt{\frac{2g}{f_D}RS} \tag{5}$$

Discharge is computed by using equation (5), and a modification of equation (3),

$$Q = \frac{\alpha A^m}{p^{m-1}} \tag{6}$$

where p is the wetted perimeter, α is $[8gS / f_D]^{1/2}$, and $m = 3/2$. A schematic drawing of a partially full circular section is shown in Figure 1. Geometric relationships for partially full conduits are further discussed in the original documentation (Woolhiser et al., 1990).

Compound Channels KINEROS2 contains the ability to route flow through channels with a significant overbank region. The channel may in this case be composed of a smaller channel incised within a larger flood plane or swale. The compound channel algorithm is based on two independent kinematic equations -- one for the main channel and one for the overbank section - that are written in terms of the same datum for flow depth. In writing the separate equations, it is explicitly assumed that no energy transfer occurs between the two sections, and upon adding the two equations the common datum implicitly requires the water surface elevation to be equal in both sections (Figure 2). However, flow may occur from one part of the compound section to another. Such transfer will take with it whatever the sediment concentration may be in that flow, when sediment routing is simulated. Each section has its own set of parameters describing the hydraulic roughness, bed slope, and infiltration characteristics. A compound channel element can be linked with other compound channels or with simple trapezoidal channel elements. At such transitions, as at other element boundaries, discharge is conserved and new heads are computed downstream of the transition.

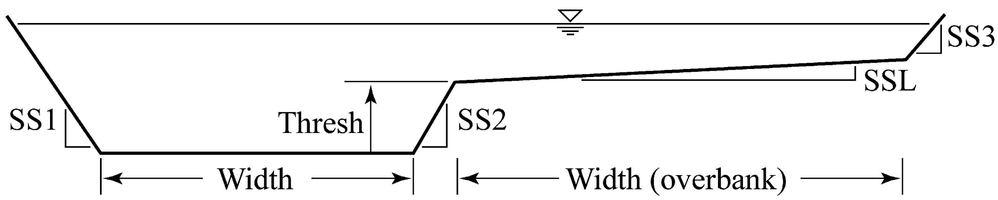

Figure 2. Compound channel section showing geometric input parameters

Base Flow KINEROS2 allows the user to specify a constant base flow in a channel, or to specify the input of a constant discharge at a point such as a spring or discharge point. This feature allows simulation of floods that occur in excess of an existing input or base discharge.

Numerical Method for Channels The kinematic equations for channels are solved by a four point implicit technique similar to that for overland flow surfaces, except that A is used instead of h, and the geometric changes with depth must be considered:

$$A_{j+1}^{i+1} - A_{j+1}^{i} + A_{j}^{i+1} - A_{j}^{i} + \frac{2\Delta t}{\Delta x}\left\{\theta_{w}\left[\frac{dQ^{i+1}}{dA}\left(A_{j+1}^{i+1} - A_{j}^{i+1}\right)\right] + \left(1-\theta_{w}\right)\left[\frac{dQ^{i}}{dA}\left(A_{j+1}^{i} - A_{j}^{i}\right)\right]\right\} - 0.5\Delta t\left(q_{c\,j+1}^{\,i+1} + q_{c\,j}^{\,i+1} + q_{c\,j+1}^{\,i} + q_{c\,j}^{\,i}\right) = 0 \tag{7}$$

where θ_w is a weighting factor for the space derivative. The terms dQ/dA are dependent only on channel geometry. Newton's iterative technique is used to solve for the unknown area A_{j+1}^{i+1}. The finite difference equation for circular conduits is written in terms of θ and is similar to equation (7) except that the lateral inflow terms (q_c) are zero.

The appropriate value of Manning's n or Chezy C to use for channels in KINEROS depends on (1) the channel material (that is, grassed waterway, gravel bedded stream, concrete-lined channel), (2) the degree to which the channel conforms to the idealized trapezoidal cross section, and (3) how straight the channel reach is. Because of these factors, choice of the appropriate parameters is highly subjective, except for artificial channels. Barnes (1967) estimated Manning's n for several streams and presented pictures of the stream reaches. These photographs are very useful in obtaining estimates for natural channels. Values of Manning's n or Chezy C for artificial channels can be obtained from several sources, including Chow (1959).

In arid and semiarid regions, infiltration into channel alluvium may significantly affect runoff volumes and peak discharge. If the channel infiltration option is selected, equation (5) is used to calculate accumulated infiltration at each computational node, beginning either when lateral inflow begins or when an advancing front has reached that computational node. Because the trapezoidal channel simplification introduces significant error in the area of channel covered by water at low flow rates (Unkrich and Osborn, 1987), an empirical expression is used to estimate an "effective wetted perimeter." The equation used in KINEROS2 is

$$p_e = min\left[\frac{h}{0.15\sqrt{BW}}, 1\right] p \tag{8}$$

where p_e is the effective wetted perimeter for infiltration, h is the depth, BW is the bottom width, and p is the channel wetted perimeter at depth h. This equation states that p_e is smaller than p until a threshold depth is reached, and at depths greater than the threshold depth, p_e and p are identical. The channel loss rate is obtained by multiplying the infiltration rate by the effective wetted perimeter. Further experience may suggest changes in the form and parameters of equation (8).

Detention Structure Routing

In addition to surface and channel elements, a watershed may contain detention storage elements, which receive inflow from one or two channels and produce outflow from an uncontrolled outlet structure. This element can represent a pond, or a flume or other flow measuring structure with backwater storage. KINEROS2 accommodates such elements. As long as outflow is solely a function of water depth, the dynamics of the storage are well described by the mass balance and outflow equations,

$$\frac{dV}{dt} - q_I - q_O - A_p f_c \tag{9}$$

and

$$q_O = C_1 \left(h_r - h_z\right)^{c_2} \tag{10}$$

in which V = $V(h_r)$ is storage volume [L^3],

h_r = water surface elevation [L],

q_I = inflow rate [L^3 /T],

q_O = outflow rate [L^3/T],

A_p = pond surface area [L^2]

f_c = pond infiltration loss rate [L/T],

h_z = outflow weir or flume zero flow elevation [L], and C_1 and c_2 = weir or orifice coefficients.

Water surface elevation (h_r) is measured from some datum below the lowest pond elevation, and $V(h_r)$ is determined from the description of the storage geometry. Equation (9) is written in finite difference form over a time interval (t) and the stage at time $t + \Delta t$ is determined by the bisection method. Equation (10) is general and can represent most control structures such as weirs, overfalls, or orifices. For weirs, C_1 must include the overfall length.

For purposes of water routing, the reservoir geometry may be described by a simple relationship between V, surface area, and h_r.

References

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