Presented at SAST Modeling Workshop
EROS Data Center, Sioux Falls, South Dakota
February 15, 1994

NWS FLDWAV Model for Real-Time Flood Routing in the Mississippi River Basin

D.L. Fread[1]

INTRODUCTION

The National Weather Service (NWS) hydrology program provides flood, daily river, and water resource forecasts to cooperating agencies at the Federal, state, and local level and to the general public. Thirteen River Forecast Centers (RFC) prepare the forecasts for dissemination.

Within the National Weather Service River Forecast System (NWSRFS), the runoff generated by rainfall-runoff models is aggregated in fairly large, well-defined channels (rivers), and then transmitted downstream by unsteady flow routing techniques of the hydrologic or storage variety. Although these routing techniques function adequately in many locations, they have serious shortcomings when the unsteady flows are subjected to significant backwater effects due to reservoirs, tides, or inflows from large tributaries. When effective hydraulic slopes of the rivers are quite mild, the flow inertial effects ignored in the hydrologic techniques become important. Also, levee overtoppings/failures add complexities which are not handled by the hydrologic routing techniques, and highly transient flows from dam breaks which often greatly exceed the flood-of-record are not treated adequately by hydrologic routing.

To improve the routing capabilities within NWS forecasting procedures, the Hydrologic Research Laboratory (HRL) has developed dynamic routing models suitable for efficient operational use in a wide variety of applications involving the prediction of unsteady flows in rivers, reservoirs, and estuaries. Two such models, Dynamic Wave Operational model (DWOPER) developed in early 1970's and enhanced in the early 1980's (Chow, et al., 1988; Fread, 1978, 1985, 1993), and DAMBRK, (Dam-Break Flood model) developed in the mid-1970's and improved throughout the 1980's (Fread, 1977, 1985, 1988, 1993), are based on an implicit finite-difference solution of the Saint-Venant one-dimensional equations of unsteady flow. More recently, a comprehensive flood routing model Flood Wave (FLDWAV) has been undergoing development and testing (Fread and Lewis, 1988; Fread, 1993); it combines the capabilities of DWOPER and DAMBRK, and provides features not contained in either of these models. The FLDWAV model will be placed in operational use on the Mississippi, Missouri, Illinois, Ohio, and Arkansas Rivers and their principal tributaries during the 1990's as part of the Water Resource Forecasting System (WARFS) implementation at NWS RFCs throughout the Mississippi River Basin.

FLDWAV MODEL DESCRIPTION

Governing Equations

The governing equations of the FLDWAV model are: (1) the expanded one-dimensional equations of unsteady flow originally derived by Saint-Venant; (2) an assortment of internal boundary

---

[1] Director, Hydrologic Research Laboratory, Office of Hydrology, National Weather Service, NOAA, 1325 East-West Highway, Silver Spring, MD 20910.

equations of flow through one or more flow control structures, such as dams, located along the main-stem river and/or its tributaries; and (3) external boundary equations of known upstream/downstream discharges or water elevations which vary either with time or each other.

Expanded Saint-Venant Equations: An expanded form of the Saint-Venant equations of conservation of mass and momentum consist of the following (Fread, 1988, 1993):

$$\partial Q/\partial x + \partial s_c(A+A_o)/\partial t - q = 0 \tag{1}$$

in which Q is discharge (flow); A is wetted active cross-sectional area; A_o is wetted inactive off-channel (dead) storage area associated with topographical embayments or tributaries; s_c is a depth-dependent channel sinuosity coefficient; q is lateral flow (inflow is positive, outflow is negative); t is time; and x is distance measured along the mean flow-path of the floodplain. The conservation of momentum equation is:

$$\partial(s_m Q)/\partial t + \partial(\beta Q^2/A)/\partial x + gA(\partial h/\partial x + S_f + S_e + S_i) + L = 0 \tag{2}$$

in which s_m is another depth-dependent sinuosity coefficient, g is the gravity acceleration constant; h is the water surface elevation; L is the momentum effect of lateral flows ($L = -qv_x$ for lateral inflow where v_x is the lateral inflow velocity in the x-direction, $L = -qQ/(2A)$ for seepage lateral outflows,$L = -q\,Q/A$ for bulk lateral outflows such as flows over levees); S_f is the boundary friction slope, i.e., $S_f = |Q|Q/K^2$ in which $K = 1.49\,AD^{2/3}S^{1/2}/n$ is the total conveyance determined by summing conveyances of the left/right floodplains and the channel in which the channel conveyance is modified by the factor, $1/s_m{}^{1/2}$, and all conveyances are determined automatically from the data input of topwidth/Manning n versus elevation tables for cross sections of the channel and left/right floodplains; S_e is the expansion/contraction slope, i.e., $S_e = k_e/(2g) \cdot \partial(Q/A)^2/\partial x$ where k_e is the expansion/contraction loss coefficient; β is the momentum coefficient for non-uniform velocity distribution and is internally computed from the conveyances and areas of the channel and left/right floodplains and S_i is the internal viscous dissipation slope appropriate only for non-Newtonian (mine tailings/mud/debris) flows.

Internal Boundary Equations: Locations along the main-stem and/or tributaries where the flow is rapidly varied in space and Eqs. (1-2) are not applicable, e.g. dams, bridges/road-embankments, short steep rapids, etc. Here, internal boundary equations are required in lieu of Eqs. (1-2), i.e.,

$$Q_i - Q_{i+1} = 0 \tag{3}$$

$$Q_i = f(h_i,\ h_{i+1},\ \text{properties of control structure}) \tag{4}$$

in which the subscripts i and i+1 indicate cross sections just upstream and downstream of the structure, respectively. For a bridge, Eq. (4) becomes:

$$Q_i = \sqrt{2g}\ C_b A_b\,(h_i - h_{i+1} + v^2/2g - \Delta h_f)^{1/2} + C_e L_e K_e (h_i - h_e)^{3/2} \tag{5}$$

in which C_b is the coefficient of flow through the bridge, A_b is the wetted cross-sectional area of the bridge opening, $v = Q_i/A_i$, Δh_f is the head loss through the bridge, C_e is the coefficient of flow over the embankment, L_e is the length of the road embankment, h_e is the elevation of the embankment crest, and K_e is a broad-crested weir submergence correction, i.e., $K_e = 1\text{-}23.8\ (r - 0.67)^3$, where $r = (h_{i+1} - h_e)/(h_i - h_e)$ if $r > 0.67$, otherwise $K_e = 1$.

If the flow structure is a dam, Eq. (4) becomes:

$$Q_i = K_s C_s L_s (h_i - h_s)^{3/2} + \sqrt{2g}\ C_g A_g (h_i - h_g)^{1/2} + K_d C_d L_d (h_i - h_d)^{3/2} + Q_t + Q_{br} = 0 \qquad (6)$$

in which K_s, C_s, L_s, and h_s are the uncontrolled spillway's submergence correction factor, coefficient of discharge, length of spillway, and crest elevation, respectively; K_d, C_d, L_d, and h_d are similar properties of the crest of the dam; C_g, A_g, and h_g are the coefficient of discharge, area, and height of opening of a fixed or time-dependent moveable gate spillway; Q_t is a constant or time-dependent turbine discharge; and Q_{br} is a time-dependent dam breach flow, i.e.,

$$Q_{br} = C_v K_b [3.1\ b_i (h_i - h_b)^{3/2} + 2.45\ z\ (h_i - h_b)^{5/2}] \qquad (7)$$

in which b_i and h_b are the known time-dependent breach bottom width and elevation, respectively, z is the side slope of the breach (1: vertical to z: horizontal), C_v is a velocity of approach correction factor, and K_b is a broad-crested weir submergence correction factor similar to K_e in Eq. (5). The instantaneous breach width is $b_i = b(\tau_b/\tau)^e$, in which b is the bottom width of the breach at peak outflow through the breach, τ_b is the time since beginning of the breach formation, τ is the total time for the breach to form, and e is an exponent $1 \leq e \leq 3$, with e usually assumed as unity (linear breach formation). Also, the instantaneous breach bottom elevation is $h_b = h_d - H_d (\tau_b/\tau)^e$, in which h_d is the elevation of the dam crest and H_d is the height of the dam.

External Boundary Equations: These are required at the upstream and downstream extremities of the waterway; they may be a specified time series of discharge or water elevation. Also, the downstream boundary can be Eq. (6), an empirical rating of h and Q, or a channel control, loop-rating based on the Manning equation in which S (the dynamic energy slope) is approximated by:

$$S = -(h_N - h_{N-1})/\Delta x - (Q - Q^{t-\Delta t})/(gA\ \Delta t) - [(Q^2/A)_N - (Q^2/A)_{N-1}]/(gA\ \Delta x) \qquad (8)$$

in which Δx is the distance between the last two, N-1 and N^th^, cross sections.

Solution Technique

In FLDWAV, the Saint-Venant Eqs. (1-2) are solved by a weighted four-point nonlinear implicit finite-difference numerical technique as described by (Fread, 1985). Substitution of appropriate simple algebraic approximations for the derivative and non-derivative terms in Eqs. (1-2) result in two nonlinear algebraic equations for each Δx reach between specified cross sections. When these are specified for each Δx reach and are combined with the external boundary equations and any necessary internal boundary equations, the combined set of equations may be solved by an iterative quadratic solution technique (Newton-Raphson) along with an efficient, compact, quad-diagonal Gaussian elimination matrix solution technique. Initial conditions required at t=0 are automatically obtained via a steady flow backwater solution provided within FLDWAV.

SPECIAL FEATURES OF FLDWAV

The FLDWAV model has several special features including: flow routing through a system of interconnected waterways, levee overtopping/floodplain interactions, an enhanced subcritical/supercritical mixed-flow solution algorithm, automatic calibration, and Kalman filter real-time updating.

Flow Through System of Waterways

The FLDWAV model can route unsteady flows occurring simultaneously in a system of interconnected waterways. Any of the waterways may contain one or more dams which control the flow and which may breach if failure conditions are reached. A river system consisting of a main-stem river and one or more principal tributaries is efficiently solved using an iterative relaxation method (Fread, 1985) in which the flow at the confluence of the main-stem and tributary is treated as the lateral inflow/outflow (q) in Eqs. (1-2). If the river consists of bifurcations such as islands and/or complex dendritic systems with tributaries connected to tributaries, etc., a network solution technique is used (Fread, 1985), wherein three internal boundary equations conserve mass and momentum at the confluence. This system of algebraic equations uses another special compact Gaussian elimination matrix technique within FLDWAV for an efficient solution.

Levee Overtopping/Floodplain Interactions

Flows which overtop levees located along either or both sides of a main-stem river and/or its principal tributaries can be treated as lateral flow (q) in Eqs. (1-2) where the diverted lateral flow over the levee is computed as broad-crested weir flow. This overtopping flow is corrected for submergence effects if the floodplain water-surface elevation sufficiently exceeds the levee crest elevation. The overtopping flow may reverse its direction when the floodplain elevation exceeds the river water-surface elevation, thus allowing flow to return to the channel after the flood peak passes. The overtopping broad-crested weir flow is computed according to the following:

$$q = -c_\ell \; K_s \; (h - h_c)^{3/2} \qquad (9)$$

where K_s is computed as in Eq. (6) except $r = (h_{fp} - h_c) / (h - h_c)$, in which c_ℓ is the weir discharge coefficient, K_s is the submergence correction factor similar to that used in Eq. (7) for dam breaches, h_c is the levee-crest elevation, h is the water-surface elevation of the river, and h_{fp} is the water-surface elevation of the floodplain. Flow in the floodplain can affect overtopping flows via the submergence correction factor, K_s. Flow may also pass from the waterway to the floodplain through a time-dependent crevasse (breach) in the levee via a breach-flow equation similar to Eq. (7). The floodplain, which is separated from the principal routing channel (river) by the levee, may be treated as: (a) a dead storage area (A_o) in the Saint-Venant equations; (b) a tributary which receives its inflow as lateral flows (the flows from the river which overtop the levee-crest) which are dynamically routed along the floodplain; and (c) the flows and water-surface elevations can be computed by using a level-pool routing method particularly if the floodplain is divided into compartments by levees (dikes) or elevated roadways located perpendicular to the river levee(s).

Supercritical/Subcritical Mixed Flow

Flow can change with either time or distance along the routing reach from supercritical to subcritical while passing through critical flow, or conversely. This "mixed flow" requires special treatment to prevent numerical instabilities in the solution of the Saint-Venant equations. FLDWAV addresses this difficulty by using a concept of avoiding the use of the Saint-Venant equations at the point where mixed flow occurs. An enhanced mixed flow algorithm automatically subdivides the total routing reach into sub-reaches wherein only subcritical or supercritical flows occur. The transition locations where flow changes from subcritical to supercritical or vice versa are treated as boundary conditions thus avoiding the application of the Saint-Venant equations to the transition flow and subsequent numerical solution difficulties. The Froude number (Fr) is used to determine the supercritical reaches where Fr > 1. At each time step, the solution proceeds sub-reach by sub-reach in the downstream direction.

Automatic Calibration

An option within FLDWAV allows the automatic determination of the Manning n such that the difference between computed water surface elevations (stage hydrographs) and observed hydrographs is minimized. The Manning n can vary with either flow or water elevation and with each sub-reach separated by water level recorders. The algorithm (Fread and Smith, 1978) for efficiently accomplishing this is applicable to a single multiple-reach river or a main-stem river and its principal tributaries. FLDWAV also provides an option (Fread and Lewis, 1986) for determining optimal n values which may for some applications eliminate the need for time-consuming preparation of detailed cross-sectional data. Approximate cross sections represented by a 2-parameter power function for the channel and another for the floodplain can be estimated from topographical maps or a few site visits. The estimated cross sections are automatically adjusted as necessary to enable optimized n values to fall within user-specified min-max ranges. Also, specific cross-sectional properties at key sections (bridges, natural constrictions, etc.) can be utilized wherever necessary.

Automatic Interpolation

The FLDWAV model can automatically provide linearly interpolated cross-sections at a user specified spatial resolution in order to increase the spatial frequency at which solutions to the Saint-Venant equations are obtained. This is often required for purposes of attaining numerical stability when (a) routing very sharp-peaked hydrographs such as those generated by breached dams, (b) when adjacent cross sections either expand or contract by more than about 50 percent, and (c) where mixed flow changes from subcritical to supercritical or vice versa.

Real-Time Updating of Model Predictions

The FLDWAV model has an option to provide optimal updating of the flood routing predictions. The updating technique is a stochastic estimator which combines the solutions of the governing equations of FLDWAV with real-time observations of river stages and modified by an extended Kalman filter gain-factor computed using an efficient matrix solution technique (Fread and Jin, 1993).

FLDWAV INPUT/OUTPUT

The FLDWAV input and output are in either English or metric (SI) units as specified at the beginning of a model run. The input conforms to a specified format with the last field of each line of data reserved for user defined identification information. The input is of the "batch" type. A special stand-alone menu-driven interactive input program is also scheduled to be available as a utility program to help the user develop the "batch" input file. Editing of existing data files is by either the menu-driven interactive program or a typical editor utility program.

The FLDWAV output consists of numerical tables and color-graphical displays. FLDWAV's color-graphical display is a separate stand-alone program written in Microsoft C. It will display the following information as determined by the user through menu-driven interactive commands: (1) peak discharge profile; (2) peak water surface elevation profile; (3) multiple discharge hydrographs at user specified cross sections (original or interpolated); (4) multiple stage hydrographs at user specified cross sections; (5) computed stage-discharge relations (including loop effect) at user specified cross sections; (6) inflow discharge hydrograph; (7) downstream boundary hydrograph or stage-discharge rating curve; (8) multiple discharge and/or water surface profiles at selected times; (9) any cross section (original or interpolated) showing (a) the active, inactive, and floodplain portions of the section, (b) the maximum water surface elevation, and (c) the user specified flooding elevation or any other elevation of interest.

REFERENCES

Chow, V.T., D.R. Maidment, and L. Mays (1988), Applied Hydrology, McGraw-Hill, New York, pp. 310-349.

Fread, D.L. (1977), "The Development and Testing of a Dam-Break Flood Forecasting Model," Proceedings of Dam-Break Flood Modeling Workshop, U.S. Water Resources Council, Washington, DC, pp. 164-197.

Fread, D.L. (1978), "NWS Operational Dynamic Wave Model," Hydrologic Res. Lab., Off. Hydrology, NWS NOAA, 66 pp.

Fread, D.L. (1985), "Channel Routing," Chapter 14, Hydrological Forecasting, (Ed.: M.G. Anderson and T.P. Burt) John Wiley & Sons, pp. 437-503.

Fread, D.L. (1988), "DAMBRK: The NWS DAMBRK Model: Theoretical Background/User Documentation," Hydrologic Res. Lab., Off. Hydrology, NWS, NOAA, 315 pp.

Fread, D.L. (1993), "Flow Routing," Chapter 10, Handbook of Hydrology, (Ed: D.R. Maidment) McGraw-Hill, New York, pp. 10.1-10.36.

Fread, D.L. and G.F. Smith (1978), "Calibration Technique for 1-D Unsteady Flow Models," ASCE, Journal Hydraulic Engr., Vol. 104, No. HY7, pp. 1027-1044.

Fread, D.L. and J.M. Lewis (1986), "Parameter Optimization of Dynamic Routing Models," Proceedings of ASCE Hydraulics Conference, Long Beach, CA, August 4-6, pp. 443-450.Fread,

D.L. and J.M. Lewis (1988), "FLDWAV: A Generalized Flood Routing Model," Proceedings of National Conference on Hydraulic Engineering, Colorado Springs, CO, 6 pp.

Fread, D.L. and Ming Jin (1993), "Real-Time Dynamic Flood Routing with NWS FLDWAV Model Using Kalman Filter Updating," Proceedings of ASCE International Symposium on Engineering Hydrology, San Francisco, CA, July 25-30, pp. 996-951.