NOAA Technical Memorandum OAR FSL-24

F2D - A KINEMATIC DISTRIBUTED WATERSHED RAINFALL-RUNOFF MODEL

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Boulder, Colorado
March 2000

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TERMS AND ACRONYMS

ALERT	Automated Local Evaluation in Real Time
BTBS	Backward in Time, Backward in Space
DEM	Digital Elevation Model
FTBS	Forward in Time, Backward in Space
GIS	Geographic Information Systems
GLUE	Generalized Likely Uncertainty Estimation
GRASS	Geographic Resources Analysis Support System
LULC	Land Use and Land Cover
TOPAZ	TOpographic PArameteriZation
UDFCD	The Denver Urban Drainage and Flood Control District
USDA	United States Department of Agriculture

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ABSTRACT: An event-based, kinematic, infiltration-excess, distributed rainfall-runoff model was developed to acknowledge and account for the spatial variability and uncertainty of several parameters relevant to storm surface runoff production and surface flow. The model, F2D (Flood Two-Dimensional), is compatible with raster Geographic Information Systems (GIS) and spatially and temporally varied rainfall data. Principal raster data inputs include hydrography data derived from a digital elevation model (DEM), soil texture, forest type, forest density, lakes, reservoirs, land use and land cover (LULC), and impervious regions within a basin. Monte Carlo simulation and a likelihood measure are utilized to calibrate the model, allowing for a range of possible system responses from the calibrated model. Using rain gauge adjusted radar-rainfall estimates, the F2D model was applied and evaluated to a limited number of historical events for a watershed within the Denver Urban Drainage and Flood Control District (UDFCD) that contains mixed land use classifications. The 95% uncertainty bounds obtained from the F2D model envelop almost all observed responses at the main basin outlet for the events considered, suggesting an acceptable model structure.

1. INTRODUCTION

Distributed-parameter rainfall-runoff models partition a basin into smaller elements in the horizontal, and possibly, also the vertical, to account for the spatial variability of processes, input, boundary conditions, and watershed characteristics relevant to runoff generation and surface flow (Singh 1995). If at least one of the hydrologic processes is based on a conservation law, or one of its approximations, in one or more space dimensions, a distributed model is classified as advanced, complex, or physically-based. Advanced distributed watershed scale surface runoff models were described by Wang and Hjelmfelt (1998), Orlandini and Rosso (1996), Garrote and Bras (1995), Julien et al. (1995), Vieux and Gauer (1994), Grayson et al. (1992), Goodrich et al. (1991), James and Kim (1990), Woolhiser et al. (1990), Beven et al. (1987), Field and Williams (1987), Abbott et al. (1986), Jayawardena and White (1979), Ross et al. (1979), and Singh and Woolhiser (1976). Arguably, these models are conceptually more correct than traditional lumped methods, not only because of their ability to incorporate large quantities of data describing model input and distributed watershed properties, but also because of their sophisticated treatment of the flow dynamics internal to a basin. In theory, the parameters for complex distributed models can be obtained from field measurements alone, allowing for their application to ungauged basins, and for their use in evaluating alternative land management strategies. Several of the advanced distributed models cited above were expressly designed to capitalize on relatively recent advances in GIS technology. The GIS serves as a spatial data management and processing environment, providing the means for mapping and evaluation at multiple scales.

Complex distributed models are typically calibrated against a historical record of observed events to compensate for uncertainties in data, model parameters, and model structure (Binley et al. 1991). Ironically, the capability to incorporate enormous quantities of spatially varied data is the clear weakness for distributed-parameter models. The large number of model parameters that may vary from cell to cell, parameter interaction, and relatively significant computational requirements make the calibration of a complex distributed model a difficult task. This was clearly illustrated in the work by Michaud (1992) and Michaud and Sorooshian (1994). In addition, their work reinforced the observation made by Beven (1989) that physical reasoning may be of little help in calibrating a physically-based distributed model. Binley et al. (1991) stated two problems related to relying upon field measurements alone to calibrate a physically-based model. The level of discretization required to maintain an accurate numerical approximation with the descriptive partial differential equation(s) may result in far too many parameters to determine by experiment or the field test may very well not exist. While optimistic about the future for distributed rainfall-runoff models, Bras (1999) noted that their calibration remains a challenge.

It is unlikely that there is a unique optimal parameter set for a specific complex distributed model structure as suggestd or observed in recent studies (Binley et al. 1991; Beven and Binley 1992; Beven 1995; Beven et al. 1995; Freer et al. 1996; Franks et al. 1998). Rather, there may be many parameter sets within a model structure that equally represent the rainfall-runoff process in terms of some subjectively chosen performance measure. Given the lack of a rigorous basis for differentiating among the numerous acceptable parameter sets, which may lie in different regions in the parameter space, Beven and Binley (1992) developed the Generalized Likely Uncertainty Estimation (GLUE) procedure as a method for model calibration and uncertainty estimation.

The GLUE methodology of Beven and Binley (1992) does not acknowledge a unique optimal parameter set. Instead, Monte Carlo simulation, a likelihood measure or set of likelihood measures, and an acceptance/rejection criterion are used to generate, evaluate, and accept or reject parameter sets as simulators of a basin's response. The likelihood measures for the accepted parameter sets are utilized to estimate the uncertainty of a model's predictions. Beven (1998) discussed four alternative methods for updating likelihood measures as additional data become available. The use of Bayes' equation has received the most attention. Beven and Binley (1992), Beven et al. (1995), Melching (1995), and Freer et al. (1996) outline the requirements for the GLUE procedure. Applications of the GLUE methodology of Beven and Binley (1992) to rainfall-runoff modeling include the work of Beven and Binley (1992), Beven et al. (1995), Freer et al. (1996), and Franks et al. (1998). Computational demands are high for the GLUE procedure; however, computational constraints have also limited the success of manually calibrating a physically-based distributed rainfall-runoff model (Michaud 1992; Michaud and Sorooshian 1994). Michaud (1992) expressed the need for an automated calibration technique that would ease the application of an advanced distributed rainfall-runoff model.

This paper describes a complex distributed rainfall-runoff model that expressly includes Monte Carlo simulation as an approach for model calibration and uncertainty estimation. The model, F2D (Flood Two-Dimensional), also allows for manual calibration. It is event-based, assumes the infiltration-excess runoff mechanism, and the kinematic wave approximation of the equations describing one-dimensional unsteady free surface flow as overland or open channel flow is used to route excess rainfall over the land surface and through an organized stream network. The F2D model is compatible with raster GIS and spatially and temporally varied rainfall data. The objectives for developing the model include the need for an advanced distributed rainfall-runoff model structure that: (1) accommodates some of the issues that have been raised regarding the calibration of such a model type, and (2) can be used to investigate/evaluate uncertainty in rainfall-runoff modeling (Uccellini 1999). Previous advanced distributed rainfall-runoff model applications of the GLUE methodology of Beven and Binley (1992) have limited the number of model parameters and negated their spatial variability for practical reasons. This study retains the spatial variability of model parameters from cell to cell. An approach is employed to incorporate slope information from a finer grid while operating at a coarser scale. The F2D model is applied to a limited number of events for a watershed within the Denver Urban Drainage and Flood Control District (UDFCD) that contains mixed land use classifications.

2. MODEL DESCRIPTION

The distributed rainfall-runoff model, F2D, operates on a square raster grid of specified spatial resolution, *L*. Julien et al. (1995) summarized several important factors related to the selection of an appropriate grid cell size when using a physically-based rainfall-runoff model. These factors include model accuracy, spatial variability of the watershed characteristics, data availability and accuracy, size of the basin, and computational effort. The primary model inputs include raster and tabular data sets describing the watershed boundary, flow direction based on the D-8 method (Fairfield and Leymarie 1991), slope, overland flow distance to the main basin outlet, the stream network; network topology; and channel geometry, forest type, forest density, soil textural classification, land use and land cover, lakes and associated surface areas, reservoirs and associated surface areas, spatially varied roughness values, initial moisture content, and impervious areas within the basin. While most GIS include tools for the derivation of hydrography data from DEMs, the F2D model relies on the topographic parameterization model TOPAZ (Garbrecht and Martz 1999). This is primarily due to the tabular output files that the TOPAZ model provides, which can be easily modified and used as input data to support hydrologic modeling (DeBarry et al. 1999).

Currently, the principal model components include spatially varied interception, accounting of input rainfall to lakes and reservoirs and routing into reservoirs, spatially varied infiltration, kinematic-wave overland flow routing, channel losses, and kinematic-wave channel flow routing. Several of the model components may be switched on or off. The main model outputs include a volume summary, discharge hydrographs for each subbasin as well as for the main basin outlet, and raster maps of various variables, such as cumulative infiltration and excess-rainfall. The model was expressly designed to support Monte Carlo simulation for a single storm event, with the intent of estimating the range of possible system responses. Parameter values related to infiltration losses and surface flow routing are based on input raster and tabular data sets, published guidelines, and field observations. The following sections describe the F2D model components, including data requirements and parameter estimation.

2.1 Rainfall

Rainfall rates may be input to the F2D model in one of two ways; either as a sequence of raster ASCII files, each of arbitrary duration, or as a spatially uniform rate of specified duration. Rainfall is partitioned to lakes or reservoirs within grid cells that contain a lake or reservoir or part of a lake or reservoir, the quantity is based on surface area. This rainfall is assumed to not contribute to direct runoff. If desired, the F2D model can generate images of rainfall over the region of interest, at periodic user-specified intervals. These images may be looped in sequence, providing an informative display of the spatial and temporal character of the rainfall for a given event.

2.2 Interception

Spatially varied interception is modeled by specifying an interception capacity within each grid cell that is based on forest type and forest density data (Powell et al. 1993; Zhu and Evans 1992) and published guidelines (Helvey 1971). This quantity is taken from the initial rainfall estimates until it is satisfied. The F2D model may be run with or without considering interception.

2.3 Infiltration

Within the F2D model, spatially-varied infiltration rates are computed using the Green and Ampt equation:

$$f = K_{ns}\left(1+\frac{\psi_f(\theta_{ns}-\theta_i)}{F}\right) \qquad (1)$$

where f, $K_{ns} = 1/2K_s$, K_s, ψ_f, θ_{ns}, θ_i, and F represent the potential infiltration rate, Green and Ampt hydraulic conductivity, saturated hydraulic conductivity, Green and Ampt wetting front capillary pressure head parameter, water content of the soil at natural saturation, initial soil moisture content, and cumulative infiltrated depth, respectively (McCuen et al. 1981; Rawls et al. 1983; Reed and Maidment 1998). During a given time step, the actual infiltration rate is determined by taking the minimum of the potential infiltration rate and the maximum available rate. The maximum available rate is calculated as the sum of the previous excess rainfall amount and the current equivalent rainfall depth divided by the time step.

The saturated hydraulic conductivity, Green and Ampt wetting front capillary pressure head parameter, water content of the soil at natural saturation, and initial soil moisture content must all be estimated to apply the Green and Ampt infiltration model. McCuen et al. (1981) determined that the parameters of the Brooks-Corey model (Brooks and Corey 1964) (porosity, ϕ, residual soil water content, θ_r, pore size distribution index, λ, and bubbling pressure, ψ_b), and the Green and Ampt model (K_s, ψ_f, θ_{ns}) vary systematically across the U.S. Department of Agriculture (USDA) soil texture classes. Reed and Maidment (1998) conducted an in-depth comparison of two significant works that related soil hydraulic properties to soil textural classification (Rawls et al. 1982; Carsel and Parrish 1988). They noted that wetting front capillary pressure head values computed using Carsel and Parrish (1988) λ and ψ_b values were more consistent with results presented in Rawls et al. (1993) than wetting front capillary pressure head values computed using Rawls et al. (1982) values. They also observed an internal inconsistency in the Rawls et al. (1982) ψ_b value for loam soil, shown in Figure 3.13 of their study. For these reasons, Reed and Maidment (1998) adopted the Carsel and Parrish (1988) values for their study.

Carsel and Parrish (1988) developed probability density functions that best fitted empirical distributions for K_s, θ_r, and the van Genuchten water retention parameters (van Genuchten 1980) α and n_{vG}, for 12 soil textural groups of the USDA classification system. No uncertainty information accompanied the average K_s values reported by Rawls et al. (1982). From the descriptive statistics provided by Carsel and Parrish (1988) for K_s, θ_r, α, and n_{vG}, the saturated hydraulic conductivity is the most variable. For these reasons, given the stated objectives, the F2D model described in this study utilizes information provided by Carsel and Parrish (1988) to support the estimation of the Green and Ampt parameters K_s, ψ_f, and θ_{ns} at each raster grid cell. The Brooks-Corey parameters λ and ψ_b are obtained from the van Genuchten parameters α and n_{vG} as shown in equations 2 and 3 (Reed and Maidment 1998).

$$\lambda = n_{VG} - 1 \tag{2}$$

$$\psi_b = 1/\alpha \tag{3}$$

The Green and Ampt wetting front capillary pressure head parameter is calculated from estimates of the Brooks-Corey parameters λ and ψ_b as shown in equation 4 (Brakensiek 1977; McCuen et al. 1981; Rawls et al. 1983; Reed and Maidment 1998).

$$\psi_f = \frac{\psi_b}{2}\left(\frac{2+3\lambda}{1+3\lambda}\right) \tag{4}$$

The water content at natural saturation, θ_{ns}, is estimated using equation 3.17 in Reed and Maidment (1998). Porosity values are assumed fixed for a given soil texture. Carsel and Parrish (1988) comment that variability for this parameter is minimal.

The infiltration component of the F2D model requires raster maps of soil textural classification and initial soil moisture content. If the initial soil moisture content is unknown, the model can generate estimates for each individual cell based on a uniform distribution, the maximum set at θ_{ns} and the minimum given by θ_r. If the model is to be calibrated manually, raster maps of initial soil moisture content, saturated hydraulic conductivity, moisture content at natural saturation, and wetting front capillary pressure head are required. If desired, the model can generate images of cumulative infiltration over the region of interest, at periodic user-specified intervals. These images may be looped in sequence, providing an informative display of the spatial and temporal character of cumulative infiltration for a given event. The model may be run with or without considering infiltration.

2.4 Overland Flow

The conservation law for one-dimensional shallow-water flow over a plane of small slope is given by

$$\frac{\partial \mathbf{v}}{\partial t} + \frac{\partial}{\partial x}\mathbf{f}(\mathbf{v}) = \mathbf{F}$$

$$\mathbf{v} = \begin{pmatrix} h \\ q \end{pmatrix} \quad \mathbf{f} = \begin{pmatrix} q \\ \dfrac{q^2}{h} + \dfrac{1}{2}gh^2 \end{pmatrix} \quad \mathbf{F} = \begin{pmatrix} i_e \\ gh(S_o - S_f) \end{pmatrix} \tag{5}$$

where x, t, h, q, g, i_e, S_o and S_f represent the distance in the flow direction, time, flow depth, flow rate per unit width, the acceleration due to gravity, excess rainfall rate, slope of the plane, and the friction slope, respectively. Within the F2D model, overland flow is routed using the kinematic wave approximation to the continuity equation and equation of motion. The kinematic wave approximation implies a unique functional relation between flow and surface water depth: $q = \alpha h^{\beta}$, with the terms α and β dependent upon whether the flow is laminar or turbulent. The conservation form for one-dimensional overland flow kinematic wave modeling is given by

$$\frac{\partial h}{\partial t}+\frac{\partial\left(\alpha h^{\beta}\right)}{\partial x}=i_e \tag{6}$$

and the linearized or characteristic form by

$$\frac{\partial h}{\partial t}+c\frac{\partial h}{\partial x}=i_e \tag{7}$$

where $c=\alpha\beta h^{\beta-1}$. The kinematic wave model does not account for the influence of downstream boundary conditions. Its application is restricted to those cases for which the kinematic wave approximation is valid (Woolhiser and Liggett 1967; Ponce et al. 1978; Morris and Woolhiser 1980; Daluz-Vieira 1983; Pearson 1989).

Each raster grid cell is discretized with a uniform vertex centered grid. The upstream boundary condition for watershed boundary raster grid cells is a zero flow depth. This boundary condition also applies to flow divides internal to the basin. For the basin interior raster grid cells and the outlet cell, the upstream boundary condition is determined by sweeping around the given cell, determining which neighboring cells flow into it, and summing the discharges from the last nodes of the incoming cells. The functional relation between depth and discharge is subsequently used to determine the depth at the upstream node for the given cell. The model uses Manning's resistance equation for turbulent flow conditions, implying $\alpha=\sqrt{S_o}/n$ and $\beta=5/3$ where n is the Manning's roughness coefficient. For laminar flow, the Darcy-Weisbach resistance law is used, implying $\alpha=8gS_o/k\nu$ and $\beta=3$, where k is a parameter related to the surface and ν is the kinematic viscosity. The parameter k varies with rainfall intensity; however, the raindrop impact is insignificant for hydraulically rough surfaces (Woolhiser 1975; Smith et al. 1995). The model does not vary k with rainfall intensity. The critical Reynolds number for transitioning from laminar to turbulent overland flow conditions is arbitrarily set at 400. Woolhiser (1975) noted that reported transition Reynolds numbers range from 100 to 1,000, with the most frequently cited in the range from 300 to 500. The algorithm accounts for the fact that the overland flow distance along a grid cell that has a diagonal flow direction is equal to $\sqrt{2}$ times the grid cell size. The computational sequence for performing overland flow calculations starts with the most upstream cell, and ends with the outlet cell.

The F2D model numerically approximates the conservative form of the kinematic wave approximation using the nonlinear forward in time, backward in space, FTBS, scheme

$$h_k^{n+1}=h_k^n-\frac{\Delta t}{\Delta x}\delta_{-}q_k^n+\Delta t\left(i_e\right)_k^n \tag{8}$$

where h_k^n represents the approximation at the point $(k\Delta x, n\Delta t)$, Δx is the uniform grid spacing along a raster cell, and $\delta_{-}q_k^n=q_k^n-q_{k-1}^n$. The nonlinear FTBS scheme is conservative, and it is consistent with the conservation law form of the kinematic wave approximation (Thomas 1999). The Courant-Friedrichs-Lewy (CFL) condition for the nonlinear FTBS scheme is

$0 \le \frac{\Delta t}{\Delta x} \max q'(h_k^n) \le 1$ for all k and n; it is a necessary condition for convergence (Thomas 1999). If the CFL condition is satisfied, the nonlinear FTBS scheme is monotone, hence an E scheme, at most first order accurate and totally variation decreasing (Thomas 1999). The cited results guarantee that the scheme will yield a weak entropy solution, in the limit, of the conservation law (equation 6), and that it will not introduce unwanted dispersive wiggles into the solution. This is an important requirement given the very shallow flow depths that are associated with overland flow (Zhang and Cundy 1989) and the possibility for shock formation at the junction of each overland flow plane. The modified partial differential equation (Warming and Hyett 1974; Thomas 1995) for the FTBS scheme, assuming c is constant and including derivatives up to and including the third order derivatives, is given by Skahill and Johnson (1999a)

$$h_t + ch_x + \frac{c\Delta x}{2}\left(1 - \frac{c\Delta t}{\Delta x}\right)h_{xx} + \frac{c\Delta x^2}{6}\left(2\frac{c\Delta t}{\Delta x} - 1\right)\left(\frac{c\Delta t}{\Delta x} - 1\right)h_{xxx} = 0 \tag{9}$$

Examining equation 9, it is apparent that the dissipation term dominates the dispersive term (Fennema and Chaudhry 1986; Thomas 1995), which is consistent with the general rule provided by Ponce (1991). Constantinides (1982) recommended the nonlinear FTBS scheme after a review of several finite difference methods related to numerically solving the kinematic wave approximation. Alternatively, the F2D model can numerically approximate the linearized or characteristic form of the kinematic wave approximation using the backward in time, backward in space, BTBS, scheme in combination with Newton's method.

$$\frac{-c_{k-1/2}^{n+1}\Delta t}{\Delta x} h_{k-1}^{n+1} + \left(1 + \frac{c_{k-1/2}^{n+1}\Delta t}{\Delta x}\right)h_k^{n+1} - i_e\Delta t - h_k^n = 0 \tag{10}$$

The sup-norm is utilized. If the norm is less than or equal to 10^{-10} meters, the iterations are assumed to have converged. The maximum number of iterations allowed is 50. The scheme is first order accurate and it is unconditionally stable when it is applied to solve a linear problem. Julien et al. (1995) summarized several factors that affect the stability of overland flow computations within a physically-based surface runoff model. These include grid size, rainfall rate and duration, slope, surface roughness, and infiltration parameters.

To model overland flow estimates of slope and surface roughness are required at each raster grid cell. Slope estimates are obtained from a DEM using the TOPAZ model of Garbrecht and Martz (1999) and the Geographic Resources Analysis Support System (GRASS) (USACERL 1993); however, any raster GIS may be used. The model requires three slope maps if Monte Carlo simulations are to be performed for a given event. The slope map obtained at the given model grid cell size as well as maps of the maximum and minimum slope within each raster grid cell. The last two maps are approximated from a DEM with a resolution that evenly divides into the given model grid cell size. These three layers are utilized to develop a triangular distribution for slope at each raster grid cell, with the probable value set at the slope value obtained at the given model grid cell size. This approach, albeit simplistic, attempts to include the information content of slope (Vieux 1993) from a finer grid while operating at a coarser scale.

Raster maps of the laminar and turbulent hydraulic resistance parameters are required if the model is to be calibrated manually. Otherwise, Manning's roughness coefficient values are estimated on the basis of published guidelines (Engman 1986; Task Committee on Hydrology Handbook 1996) and reclassified LULC data based on the Anderson Level II land use classification scheme (Anderson et al. 1976). With the exception of the more specific codes under the general category of urban or built-up land, the reclassification of the original Anderson Level II codes involved neglecting the second of the two integers from the original code. The ranges that are specified within the model for Manning's roughness values for the reclassified LULC data are shown in Table 2-1. If Monte Carlo simulations are to be performed for a given event, uniform random sampling is used to generate Manning's roughness values at each grid cell. The sampling may be completely random from cell to cell, or, for a given simulation, the same randomly generated value can be assigned to all cells with the same reclassified LULC code. This sampling approach equally applies to the random generation of Green and Ampt infiltration parameters; however, the estimates are based on soil texture classification. At present, the model does not include uncertainty information regarding the resistance parameter, *k*, for laminar overland flow. Estimates for *k* are based on published guidelines (Woolhiser, D.A. 1975). If Monte Carlo simulations are to be performed for a given event, for turbulent overland flow, a triangular distribution is used to estimate the exponent in the functional relation between depth and discharge at each grid cell, with the most likely value set equal to 5/3 (Chow 1959).

Table 2-1. Ranges for Manning's roughness coefficient values based on land use.

Reclassified Land Use Code (1)	Description (2)	Manning's *n* Minimum (3)	Manning's *n* Maximum (4)
11	Residential	0.010	0.30
12	Commercial and Services	0.010	0.03
13	Industrial	0.010	0.03
14	Transp., Communications, Utilities	0.010	0.03
15	Industrial and Commercial Complexes	0.010	0.03
16	Mixed Urban or Built-up Land	0.010	0.30
17	Other Urban or Built-up Land	0.010	0.30
2	Agricultural Land	0.010	0.50
3	Rangeland	0.010	0.32
4	Forest Land	0.120	0.25
5	Water	0.016	0.14
6	Wetland	0.050	0.50
7	Barren Land	0.010	0.45
8	Tundra	0.01-0.5	0.50

Percent impervious cover is associated with the Anderson level II land use codes 11-17. For code 11, the percent impervious cover may range anywhere from 20 to 65 percent (Chow et al. 1988). The estimates for the remaining codes are fixed at the quantities provided in in Reed and Maidment (1998). The F2D model computes infiltration rates and cumulative infiltration at each node within every raster grid cell within the watershed mask. These quantities may vary from node to node within a cell, as may overland flow depth. The F2D model incorporates an estimate for percent impervious cover, X, by performing infiltration computations for only the first 100 - X percent of the nodes within a raster grid cell. Computations are performed in the direction of flow. For raster grid cells with an Anderson level II land use code 11, uniform random sampling is used to generate an estimate for percent impervious cover if Monte Carlo simulations are to be performed for a given event.

The overland flow component of the F2D model requires raster maps of the basin mask, flow direction, slope, distance to the main watershed outlet, land use and land cover, and surface roughness. If desired, the model can generate images of rainfall excess over the region of interest, at periodic user-specified intervals. These images may be looped in sequence, providing an informative display of the spatial and temporal character of excess rainfall for a given event. The model may be run with or without considering overland flow; if overland flow is not modeled, channel flow cannot be modeled.

2.5 Channel Flow

The continuity equation for one-dimensional open channel flow is given by

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_l \tag{11}$$

where x, t, A, Q, and q_l represent the distance in the flow direction, time, the channel flow cross-sectional area, total discharge in the channel, and lateral inflow or outflow rate per unit length, respectively. The F2D model routes channel flow using the kinematic wave approximation to the continuity equation and equation of motion. This implies a unique functional relation between channel discharge and flow cross-sectional area. Manning's equation is used

$$Q=\frac{1}{n}AR_h^{2/3}\sqrt{S} \tag{12}$$

where n, R_h, and S represent the channel Manning's n value, hydraulic radius, and the slope of the channel bottom, respectively.

Each raster grid cell that is designated as part of the channel network consists of two contributing overland flow planes and a channel that passes through the middle of the cell, as shown in Figure 2-1. These grid cells are essentially treated as a symmetrical V-shaped basin with a stream. Input rainfall to the cell is directly applied to the channel and also to the overland flow plane portions of the grid cell, and overland flow is routed orthogonal to the channel flow direction. The slope of the two contributing overland flow planes within a channel grid cell is determined by multiplying the cell's slope value by a multiplicative constant. This value is designated by the model user and is uniformly applied to all raster grid cells that are part of the stream network. However, if Monte Carlo simulations are to be performed for a given event, the slope for the two contributing overland flow planes is based on uniform random sampling with the minimum and maximum set at the minimum and maximum slope within the cell, respectively. Channel cross sections may be approximated as a nonsymmetrical trapezoid or a rectangle. For a rectangular cross section, equation 11 reduces to

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}=\frac{q_l}{b} \qquad (13)$$

where h, u, and b represent the channel flow depth, flow velocity, and the channel width, respectively.

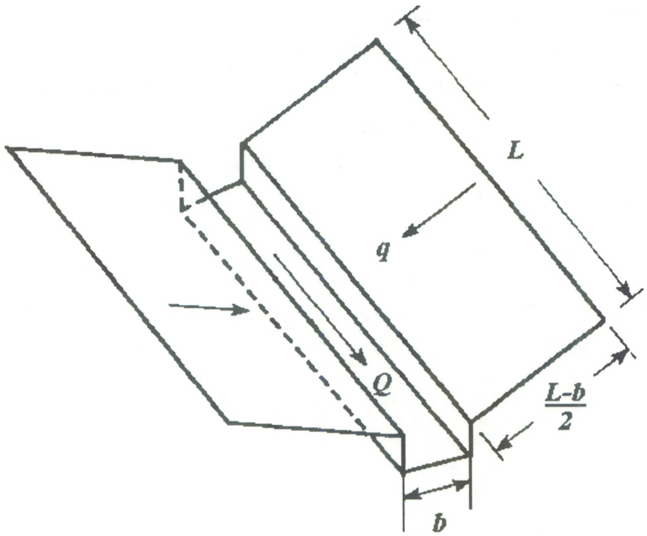

Figure 2-1. A channel grid cell with a rectangular cross section.

The computational sequence for performing channel routing computations is based on a tabular file provided by the TOPAZ model of Garbrecht and Martz (1999); which is based on stream order. The file is modified to include additional physical information describing channel geometry and Manning's *n* values for each individual channel link. The upstream boundary condition for first-order streams is based on the overland flow rate entering the cell. The continuity equation serves as the boundary condition at channel junctions. Streamflow is routed into reservoirs located along the channel network. For channels with rectangular cross-sectional areas, equation 13 may be numerically approximated using either the nonlinear FTBS scheme or the BTBS scheme in combination with Newton's method. For channels with trapezoidal cross-sectional areas, equation 11 is numerically approximated using the BTBS scheme in combination with Newton's method.

Manning's *n* values for channels are estimated on the basis of field observations and published guidelines (Chow 1959; Barnes 1967). If Monte Carlo simulations are to be performed for a given event, the Manning's *n* value for each channel is estimated from a triangular distribution, with the extremes typically set at 0.01 and 0.1 (Huang and Warner 1995). The channel routing component of the model requires raster maps of flow direction, the channel network, slope, surface roughness, and reservoirs. A tabular file describing the channel network is also required. The model can be run without channel routing. Channel losses may be computed using equation 1.

3. MODEL APPLICATION

The overland flow routing component of the F2D model was tested against the analytical solution of the kinematic wave approximation for a simple one-dimensional plane geometry. The model was applied to a 100 m long impervious plane, with a slope of 0.002, and a Manning's *n* value of 0.01. A uniform rainfall rate of 2.54 cm/h was applied for one half-hour. The initial profile was a dry surface and the critical Reynolds number for the transition from laminar to turbulent overland flow conditions was temporarily set to zero. The hydrographs obtained from the model using ten raster grid cells, each cell discretized with 11 nodes are shown in Figure 3-1, along with the analytical solution. Examining Figure 3-1, it is apparent that the model's two overland flow routing methods provide excellent agreement with the analytical solution.

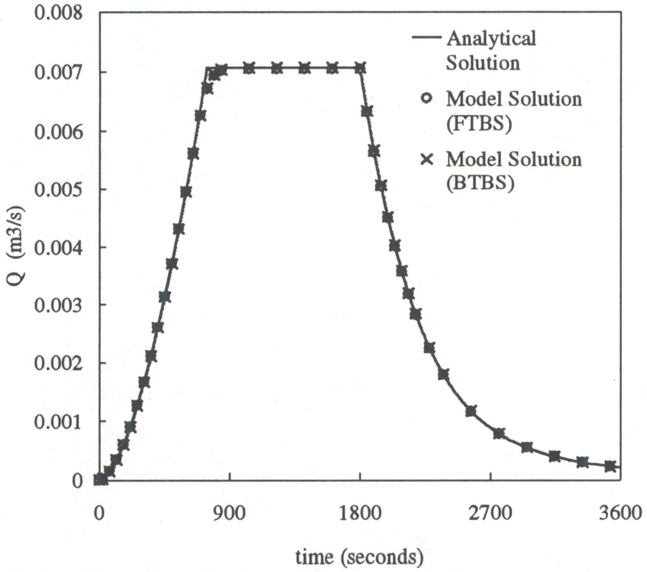

Figure 3-1. Comparison of model results with the analytical solution for a one-dimensional plane geometry.

The connectivity of the overland flow and channel flow components of the F2D model was tested by temporarily removing the channel routing call in the model code, applying a uniform excess rainfall rate for a finite duration to a basin, and simulating overland flow and channel flow routing. This was performed for a simple V-shaped basin as well as a more complicated channel network. For both cases, all of the input excess rainfall was accounted for in the channel(s) of the basin at the end of the simulation. The more complicated network, shown in Figure 3-2, was obtained from a DEM with a horizontal resolution of 100 m using the TOPAZ model of Garbrecht and Martz (1999). It is for the Buffalo Creek watershed, a basin with a drainage area of approximately 130 square kilometers located in the Rocky Mountain foothills approximately 35 miles southwest of Denver, Colorado. This basin has served as a case study site during model development and testing (Skahill and Johnson 1999b,c).

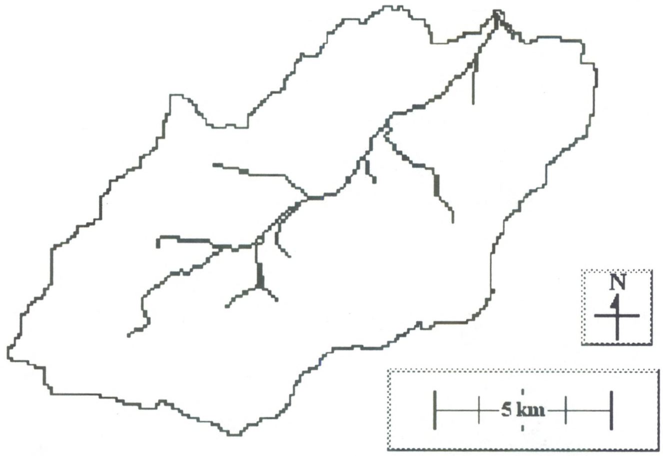

Figure 3-2. Derived channel network for the Buffalo Creek basin used to support model testing.

Constantinides and Stephenson (1982) developed dimensionless runoff hydrographs for three basin geometries: a sloping plane, a converging surface, and a V-shaped basin. They also presented computer models for each case. Comparing F2D model output with the dimensionless hydrograph solution of Constantinides and Stephenson (1982) for a V-shaped basin further tested the overland flow and channel flow components of the model. The rectangular channel had a width of 1 m, and the basin area was $100^2\ m^2$. The slope for the channel and contributing planes was set at 0.05. Manning's *n* values for the channel and contributing planes were set at 0.03 and 0.04, respectively. The initial profile was a dry surface and the critical Reynolds number for the transition from laminar to turbulent overland flow conditions was temporarily set to zero. A uniform excess rainfall rate of 2.54 cm/h was applied for one half-hour. The hydrographs obtained from the model using nine raster grid cells ($L = 33.\overline{3}$ m), each cell discretized with eleven nodes, are shown in Figure 3-3, along with the dimensionless hydrograph solution of Constantinides and Stephenson (1982) for the V-shaped basin. There are only slight differences between the model solutions and the dimensionless hydrograph solution of Constantinides and Stephenson (1982). These are attributed to assumptions made by Constantinides and Stephenson (1982) that were used to compute the dimensionless hydrograph solution for a V-shaped basin, particularly, the assumed form of the flow resistance equation for the channel and the assumption that the channel area is small compared to the plane area. The F2D model described in this paper applies input rainfall directly to a channel.

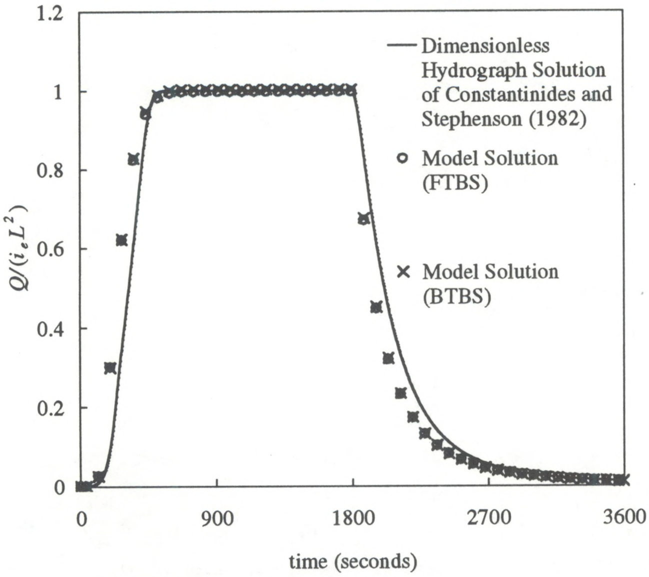

Figure 3-3. Comparison of model results with the dimensionless hydrograph solution of Constantinides and Stephenson (1982) for a V-shaped basin.

The F2D model was applied to route storm surface runoff from the Ralston Creek basin, a watershed located within the UDFCD with a drainage area of approximately 225 km^2. Elevations range from about 3138 m at the high point on the western edge of the basin to 1622 m at the watershed outlet. The basin is oriented primarily west to east. The main channel length of Ralston Creek is around 42 km, with an average slope of approximately 2.8%. The upper portions of the basin drain into Ralston reservoir, and are predominantly classified as rangeland or forestland with loam soils. The lower portion of the basin is urbanizing, and the primary soil type is silt loam. The main channel length of Ralston Creek below Ralston reservoir is around 14.8 km, with an average slope of approximately 1.3%.

Six events were selected for study to illustrate F2D model application. Storm event dates and the radar names and locations used to obtain rainfall estimates are provided in Table 3-1. Three of the events were used for model calibration (storms 1 to 3), and the remaining three events were used for model validation (storms 4 to 6). The grid cell spacing of the radar reflectivity data was 1.25 km × 1.25 km for the two storms from 1991 and 1 km × 1 km for the events from 1996 and 1997. The temporal resolution of the radar reflectivity data was approximately 6 minutes. The *Z-R* power law relationship

$$Z = 500R^{1.3} \tag{14}$$

where *Z* and *R* represent the radar reflectivity (in mm^6/m^3) and rainfall rate (in mm/hr), respectively, was used to transform reflectivity into rainfall rate. This *Z-R* relation has been used with reasonable success for the summertime climate of the Colorado Front Range (Smith and Lipschutz 1990; Sherman and Johnson 1992). A reflectivity threshold of 53 dBZ was applied before converting to a rainfall rate (Fulton et al. 1998).

Table 3-1. Storm Events Evaluated and Radar Locations.

Storm Number (1)	Storm Date (2)	Radar		
		Name (3)	Location	
			Latitude (4)	Longitude (5)
1	June 1, 1991	Mile High Radar	39.8782 N	104.759 W
2	May 26, 1996	Denver (FTG)	39.7870 N	104.546 W
3	August 4, 1997	Denver (FTG)	39.7870 N	104.546 W
4	July 22, 1991	Mile High Radar	39.8782 N	104.759 W
5	August 26, 1996	Denver (FTG)	39.7870 N	104.546 W
6	September 18, 1996	Denver (FTG)	39.7870 N	104.546 W

A bias correction factor was computed for each storm event based on the ratio of the precipitation measured by the rain gauges to the precipitation measured by the radar. Winchell et al. (1998) and Fulton (1999) used this approach in their studies. Rain gauge adjusted radar-rainfall estimates were subsequently determined by multiplying the original radar-rainfall estimates by the correction factor. The computed bias correction factor was specific to the region containing the Ralston Creek basin. For a given event, all or some of the UDFCD's Automated Local Evaluation in Real Time (ALERT) rain gauges for the Ralston Creek basin, as shown in Figure 3-4, were used to compute the bias correction factor.

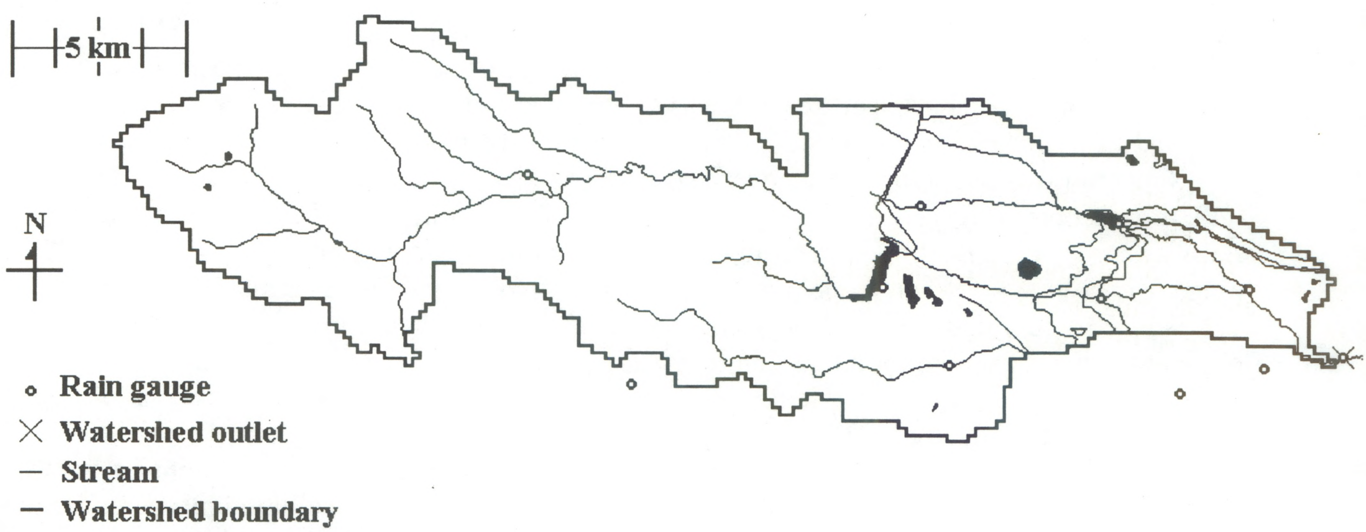

Figure 3-4. Rain gauges used in the study to compute a bias correction factor for the radar-rainfall data for a storm.

The hydrology component of the model GLEAMS was used to estimate initial soil water content for the F2D model simulations (Knisel et al. 1993; Knisel and Williams 1995). The approach was quite similar to the method used by Michaud (1992) and Michaud and Sorooshian (1994). The GLEAMS model operates on a daily time step and computes potential evapotranspiration using either the Priestly-Taylor method or the Penman-Monteith method. The option to input mean daily temperature was used, the Penman-Monteith method was selected for computing potential evapotranspiration, and the forest option of the GLEAMS model was utilized where appropriate. Raster GIS data layers describing elevation, hydrologic soil group, land use and land cover, percent clay, percent silt, and soil texture were used together with published guidelines (Saxton et al. 1986; Chow et al. 1988; Knisel et al. 1993) to estimate values for the parameters relevant to the hydrology component of the GLEAMS model. The raster GIS data layers describing percent clay, percent silt, and soil texture (Miller and White 1998) were used to determine the number of computational soil layers. Monthly averages for dewpoint temperature, solar radiation, and wind movement were based on values provided in the GLEAMS model supplemental database. The hydrology component of the GLEAMS model is not sensitive to these values (Knisel et al. 1993). GLEAMS model simulations began on January 1, 1991 and ended on December 31, 1997. Separate computations were performed at 17 locations within and surrounding the UDFCD. Irrigation was not included. Two initial estimates of soil water content were considered: field capacity and wilting point. There was little sensitivity to the initial estimate of soil water content, as noted in the GLEAMS model User Manual for long-term simulations (Knisel et al. 1993). Water content was interpolated to model grid cells using the GRASS GIS command s.surf.tps, which utilizes spline with tension. The approach used to estimate initial soil water content accounts for only gross space and time variations in soil water content (Michaud 1992; Michaud and Sorooshian 1994).

Two hundred and fifty Monte Carlo simulations were performed for each of the six events listed in Table 3-1. Estimates for the Green and Ampt parameters, Manning's *n* and slope values for overland flow planes and channels, β for turbulent overland flow conditions, and percent impervious cover were randomly generated at each model raster grid cell for each Monte Carlo simulation. The parameter values generated for the first event that was considered were subsequently used for the following five events. This supported application of the GLUE procedure of Beven and Binley (1992) for subsequent model calibration and uncertainty estimation. The chosen grid cell spacing was of a regional scale, 800 m. Interception, infiltration, overland flow, and channel flow were all considered for the model simulations. The nonlinear FTBS method was selected to route overland flow and channel flows. For application of the GLUE procedure of Beven and Binley (1992), the Nash and Sutcliffe (1970) efficiency criterion, *ES*, was used for the likelihood measure and the rejection criteria was set at 0.3. Values of *ES* range from 1 to $-\infty$. When model predictions equal observed values, *ES* equals 1. Negative values of *ES* imply that the model's predictive power is worse than using the mean of the observed values. The likelihood distribution was updated using a fuzzy union (Beven 1998) rather than Bayes' equation, due to the relatively small number of Monte Carlo simulations that were performed to illustrate F2D model application.

Table 3-2 summarizes the Nash and Sutcliffe (1970) efficiency scores obtained from the F2D model for the calibration and validation events. The normalized likelihood measures for the retained models were used to compute a weighted value for runoff volume, peak discharge, and time to peak. The 95% uncertainty bounds obtained from the model for the six events that were considered to illustrate model application are shown in Figures 6 -11. While based on a limited number of Monte Carlo simulations and considered events, the model results presented in Table 3-2 and Figures 3-5 - 3-10 are quite good. While using rain gauge adjusted radar-rainfall estimates and operating at a coarse spatial scale, the F2D model was very accurate in simulating time to peak and runoff volume, and reasonably accurate in simulating peak discharge. On average, 99.99% of the input rainfall was accounted for as either rainfall partitioned to lakes or reservoirs, interception, infiltration, rainfall excess routed into reservoirs, rainfall excess remaining on the basin, or volume out of the main basin. Examining Figures 6 - 11, the 95%

uncertainty bounds obtained from the F2D model envelop almost all observed responses at the main basin outlet for the events considered, suggesting an acceptable model structure.

Table 3-2. Model Calibration and Validation of Nash and Sutcliffe Efficiency Scores for Runoff Volume, Peak Discharge, and Time to Peak.

	Runoff Volume (1)	Peak Discharge (2)	Time to Peak (3)
Calibration	0.86	0.97	0.93
Validation	0.81	0.10	0.97

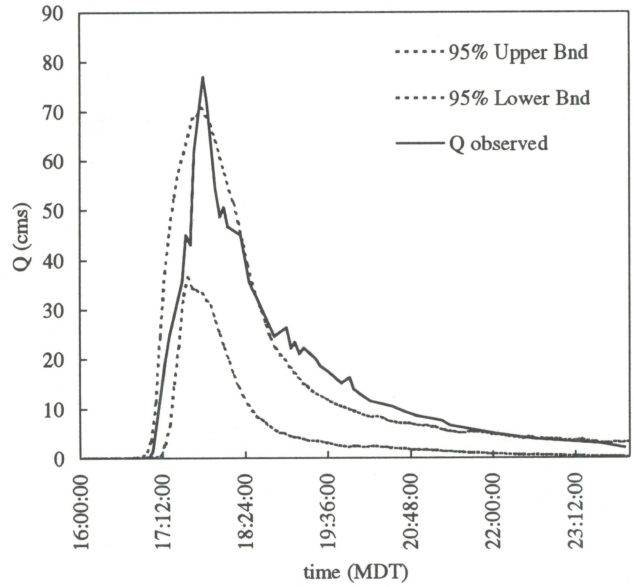

Figure 3-5. Ninety-five percent uncertainty bounds obtained from the model for the June 1, 1991 storm on the Ralston Creek basin.

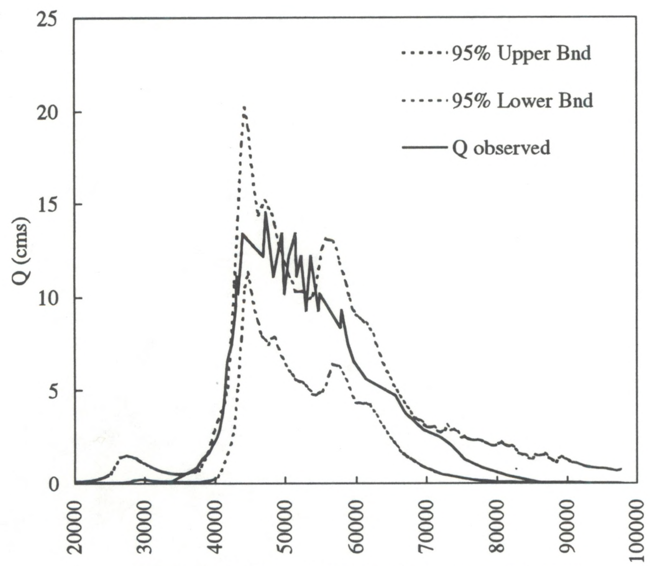

Figure 3-6. Ninety-five percent uncertainty bounds obtained from the model for the May 26, 1996 storm on the Ralston Creek basin.

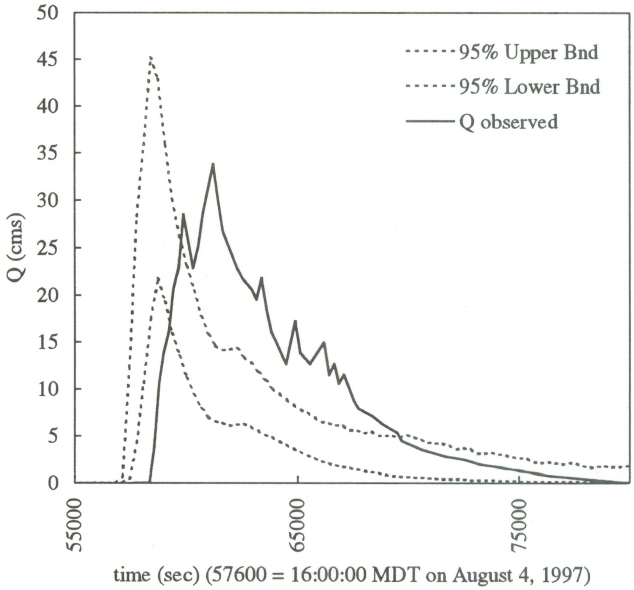

Figure 3-7. Ninety-five percent uncertainty bounds obtained from the model for the August 4, 1997 storm on the Ralston Creek basin.

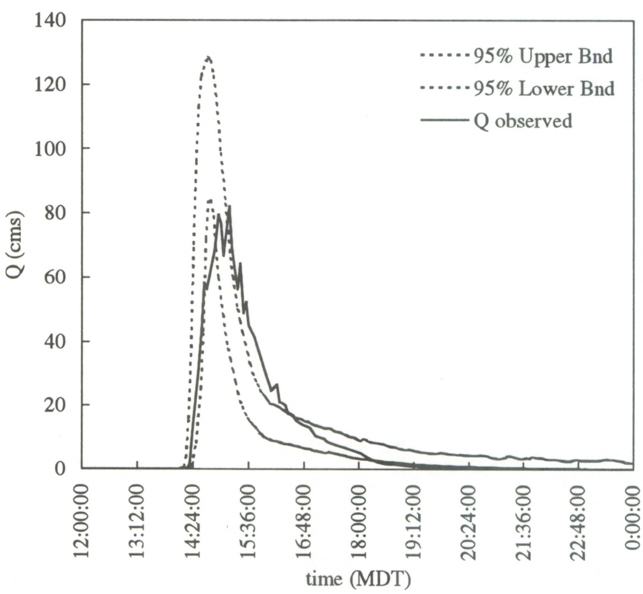

Figure 3-8. Ninety-five percent uncertainty bounds obtained from the model for the July 22, 1991 storm on the Ralston Creek basin.

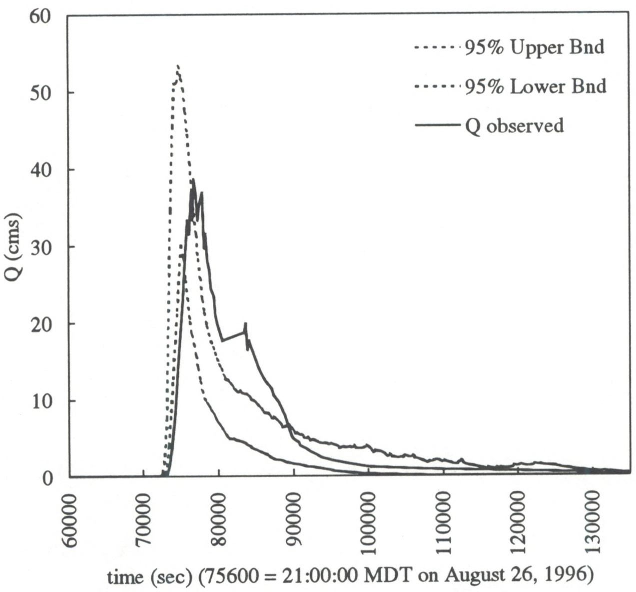

Figure 3-9. Ninety-five percent uncertainty bounds obtained from the model for the August 26, 1996 storm on the Ralston Creek basin.

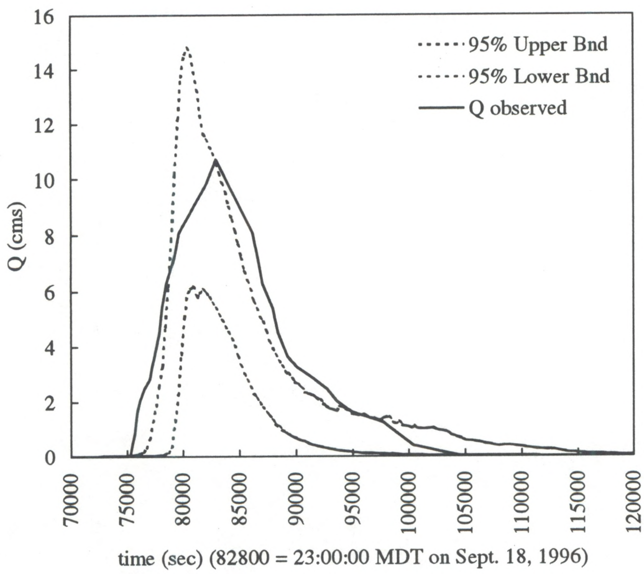

Figure 3-10. Ninety-five percent uncertainty bounds obtained from the model for the September 18, 1996 storm on the Ralston Creek basin.

4. CONCLUSIONS

This paper described an infiltration-excess distributed rainfall-runoff model that acknowledges and accounts for the spatial variability and uncertainty of several parameters relevant to storm surface runoff production and surface flow. The F2D model was expressly designed to include Monte Carlo simulation for a single storm event, with the intent of supporting model calibration and uncertainty estimation activities utilizing the GLUE methodology of Beven and Binley (1992). The described model structure addresses some of the issues that have been raised regarding the calibration of an advanced distributed surface runoff model, and it can be used to investigate/evaluate uncertainty in rainfall-runoff modeling. The F2D model is flexible in that it can also support a manual calibration, if desired.

The F2D model routes excess rainfall over the land surface and through an organized stream network using the kinematic wave approximation of the equations describing one-dimensional unsteady free surface flow as overland or open channel flow. The kinematic wave approximation may be numerically approximated using either the nonlinear FTBS method or the BTBS method in combination with Newton's method. The model's two overland flow routing methods were shown to provide excellent agreement with the analytical solution when it was applied to a simple one-dimensional impervious plane. The connectivity of the overland flow and channel flow components of the model was tested and shown to be mass conservative, as were each of the model's individual components. The overland flow and channel flow components of the model were compared against the dimensionless hydrograph solution of Constantinides and Stephenson (1982) for a V-shaped basin.

Using rain gauge adjusted radar-rainfall estimates, the F2D model was applied to route storm surface runoff from a 225 km^2 basin located within the UDFCD. The GLUE methodology of Beven and Binley (1992) was used to support model calibration and uncertainty estimation. In contrast to previous advanced distributed rainfall-runoff model applications of the GLUE methodology of Beven and Binley (1992), the model retained the spatial variability of model parameters from cell to cell. While based on a limited number of Monte Carlo simulations and considered events, the F2D model results were quite positive, particularly given the rather coarse spatial scale that was used.

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APPENDIX. NOTATION

The following symbols are used in this paper:

A	=	channel flow cross-sectional area;
b	=	channel width;
c	=	kinematic wave celerity;
ES	=	Nash and Sutcliffe efficiency criterion
F	=	cumulative infiltrated depth;
f	=	infiltration rate;
g	=	acceleration due to gravity;
h	=	flow depth;
i_e	=	excess rainfall rate;
K_{ns}	=	Green and Ampt hydraulic conductivity;
K_s	=	saturated hydraulic conductivity;
k	=	resistance parameter for laminar overland flow;
L	=	raster grid cell resolution;
n	=	Manning's roughness coefficient;
n_{VG}	=	van Genuchten water retention parameter;
Q	=	discharge in the channel;
q	=	flow rate per unit width;
q_l	=	channel lateral inflow or outflow rate per unit length;
R	=	rainfall rate;
R_h	=	hydraulic radius;
S	=	slope of the channel bottom;
S_f	=	friction slope;
S_o	=	slope of the plane;
t	=	time;
u	=	channel flow velocity;
X	=	percent impervious cover for a raster grid cell;
x	=	distance in the flow direction;
Z	=	radar reflectivity;
α	=	van Genuchten water retention parameter; coefficient in flow resistance equation;
β	=	exponent in flow resistance equation;
Δt	=	time increment;
Δx	=	spatial x-increment;
δ_-	=	backward difference operator;
ϕ	=	porosity;
λ	=	pore size distribution index;
ν	=	kinematic viscosity;
θ_i	=	initial soil moisture content;
θ_{ns}	=	water content of the soil at natural saturation;
θ_r	=	residual soil water content;
ψ_b	=	bubbling pressure;
ψ_f	=	Green and Ampt wetting front capillary pressure head parameter;

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