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WILDLAND RESOURCES CENTER
DIVISION OF AGRICULTURE AND NATURAL RESOURCES
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DIFFUSION HYDRODYNAMIC MODEL FOR FLOODPLAIN MODELING

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During floods water spills out of stream channels and overflows adjacent floodplains. Most computer models used for floodplain analysis do not accurately model this process since they assume that the flow is one-dimensional, when in actuality the flow is often highly two-dimensional. This paper describes a practical two-dimensional model for the analysis of unsteady flow on floodplains. It is based on the diffusion formulation of the equations governing unsteady flow in open channels and provides a major advance in modeling capabilities over conventional and simpler methods such as the kinematic wave method. The model includes two diffusion-routing submodels: a topographic model of the overland flow processes on the floodplain and a channel routing model which simulates the passage of the flood wave in the stream channels. Because the model flow routing technique is diffusive, backwater and ponding effects are automatically included. The model also simulates hydraulic conditions at junctions, inflow to and outflow from channels, critical depth control points, and stage-discharge controls. An example of the use of the model is included.

Voluntary Papers (Abstracts)

Poster Presentations

Exhibitors

DIFFUSION HYDRODYNAMIC MODEL FOR FLOODPLAIN MODELING

J. J. DeVries[1] and T. V. Hromadka II[2]

ABSTRACT

During floods water spills out of stream channels and overflows the adjacent floodplains. Most computer models used for floodplain analysis do not accurately model this process since they assume that the flow is one-dimensional, when in actuality the flow in many cases is highly two-dimensional. This paper describes a practical and useful two-dimensional model for the analysis of unsteady flow on floodplains. The computer model is based on the diffusion formulation of the equations which govern unsteady flow in open channels, and it provides a major advance in modeling capabilities over conventional and simpler methods such as the kinematic wave method. The model includes two diffusion routing submodels; a topographic model of the overland flow processes on the floodplain, and a channel routing model which simulates the passage of the flood wave in the stream channels. Because the model flow routing technique is diffusive, backwater and ponding effects are automatically included. Other channel system effects which the model simulates are: hydraulic conditions at junctions, inflow to and outflow from the channels, critical depth control points, and stage-discharge controls. An example of the use of the model will also be provided.

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INTRODUCTION

Currently available techniques for analysis of floodplain flows are not able to to represent unsteady backwater effects in channels and overland flow, unsteady overflows in channel systems due to constrictions (e.g., culverts, bridges, etc.), unsteady flow of floodwater across watershed boundaries due to two-dimensional (horizontal plane) backwater, and ponding effects.

In this paper, we report on the current state of development of a Diffusion Hydrodynamic Model (DHM) which approximates all of the above hydraulic effects for channels and overland surfaces, and also provides for the interfacing of these two hydraulic systems to represent channel overflow and return flow. The overland flow effects are modeled by a two-dimensional unsteady flow hydraulic model based on the diffusion form of the governing flow equations. Similarly, channel flow is modeled using a one-dimensional unsteady flow hydraulic model based on the diffusion equation. The resulting models both approximate unsteady supercritical and subcritical flow (without the user predetermining hydraulic controls), backwater flooding effects, and escaping and returning flow from the two-dimensional overland flow model to the channel system.

The current simple version of the DHM has been successfully applied to a collection of one- and two-dimensional unsteady flows hydraulic problems including dam-break analyses and flood system deficiency studies. Consequently, the DHM promises to provide a highly useful, accurate, and simple-to-use computer model which of immediate help to hydrologists and flood control engineers (however, a relatively large amount of topographic data may be needed depending of the area being modeled).

Background

One approach to studying flood wave propagation is to simply estimate a maximum possible flow rate and route this flow as a steady state flow through the downstream reaches. This method can be excessively conservative in that all effects due to the time variations in channel storage and routing are neglected.

A better approach is to use the one-dimensional (1-D) full dynamic unsteady flow equations (e.g., St. Venant eqs.). Some sophisticated 1-D models include additional terms and parameters to account for complexities in prototype reaches which the basic flow equations cannot adequately handle. However, the ultimate limit of the 1-D model can only be overcome by extending the analysis into the two-dimensional (2-D) realm. Several 2-D models employing full dynamic equations have been developed. Among them is one by Katopodes and Strelkoff[6] aimed at flood flow analysis. Attendant with the increased power and capacity of 2-D fully dynamic models, are greatly increased boundary, initial, geometry and other input data requirements and the need for large amounts of computer memory and computational speed, as well as increased computational time. Although it is often claimed that the extra computational cost and effort required for a more sophisticated model is negligible compared with the total modeling effort and cost in the 1-D realm, the application of 2-D models using the full equations of motion is not practical at present.

The coupled 1-D and 2-D diffusion hydrodynamic model (DHM) described in this paper appears to offer a simple and economic means for the estimation of flooding effects for diverging flood flows, however.

ONE-DIMENSIONAL MODEL FOR UNSTEADY FLOW

Generally, the 1-D flow approach used wherever there is no significant lateral variation in the flow. Land[7] examines four such unsteady flow models in their prediction of flooding levels and flood wave travel time, and compares the results against observed unsteady flow data. Although many dam-break studies involve flood flow regimes which are truly two-dimensional (in the horizontal plane), the 2-D case has not received much attention in the literature. In addition to the model of Katopodes and Strelkoff[6], which relies on the complete 2-D dynamic equations, Xanthopoulos and Koutitas[9] use the diffusion model to approximate a 2-D flow field. The model assumes that the flood plain flow regime is such that the inertia terms are negligible. In a 1-D model, Akan and Yen[1] also use the diffusion approach to model hydrograph confluences at channel junctions. In the latter study, comparisons of model results were made between the diffusion model, a complete dynamic wave model solving the total equation system, and the basic kinematic wave equation model. The agreement between the diffusion model and the dynamic wave model was good for the study cases, and only minor discrepancies were shown.

MATHEMATICAL DEVELOPMENT FOR TWO-DIMENSIONAL MODEL

The set of (fully dynamic) 2-D unsteady flow equations consist of one equation of continuity

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial H}{\partial t} = 0 \qquad (1)$$

and two equations of motion

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{h}\right) + gh\left(S_{fx} + \frac{\partial H}{\partial x}\right) = 0 \qquad (2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q_y^2}{h}\right) + \frac{\partial}{\partial h}\left(\frac{q_x q_y}{h}\right) + gh\left(S_{fy} + \frac{\partial H}{\partial y}\right) = 0 \qquad (3)$$

in which q_x, q_y are flow rates per unit width in the x,y-directions; S_{fx}, S_{fy} represent friction slopes in x,y-directions; H, h, g stand for, respectively, water-surface elevation, flow depth, and gravitational acceleration; and x,y,t are spatial and temporal coordinates.

The above equation set is based on the assumptions of constant fluid density with zero sources or sinks in the flow field, hydrostatic pressure distributions, and relatively uniform bottom slopes.

The local and convective acceleration terms can be grouped together such that

$$m_z + \left(S_{fz} + \frac{\partial H}{\partial z} \right) = 0, \; z = x,y \tag{4}$$

where m_z represents the sum of the first three terms in Eqs. (2) and (3) divided by gh. Assuming the friction slope to be approximated by steady flow conditions, the Manning's formula in the U.S. customary units can be used to estimate q_z

$$q_z = \frac{1.486}{n} h^{5/3} S_{fz}^{\;1/2}, \; z = x,y \tag{5}$$

Equation 5 can be rewritten as

$$q_z = -K_z \frac{\partial H}{\partial z} - K_z m_z, \; z = x,y \tag{6}$$

where

$$K_z = \frac{1.486}{n} h^{5/3} \Big/ \left| \frac{\partial H}{\partial s} + m_s \right|^{1/2}, \; z = x,y \tag{7}$$

The symbol s indicates the flow direction which makes an angle $\theta = \tan^{-1} (q_y/q_x)$ with the +x-direction.

Values of m are assumed negligible by many investigators[1,2], resulting in the simple diffusion model:

$$q_z = - K_z \frac{\partial H}{\partial z}, \; z = x,y \tag{8}$$

The proposed 2-D flood flow model is formulated by substituting Equation 8 into Equation 1,

$$\frac{\partial}{\partial x} K_x \frac{\partial H}{\partial x} + \frac{\partial}{\partial y} K_y \frac{\partial H}{\partial y} = \frac{\partial H}{\partial t} \tag{9}$$

NUMERICAL MODEL FORMULATION (GRID ELEMENTS)

For uniform grid elements, the numerical modeling approach used is the integrated finite difference version of the nodal domain integration (NDI) method. For grid elements, the NDI nodal equation is based on the usual nodal system (see Fig. 1). Flow rates along the boundary Γ are estimated using a linear trial function assumption between nodal points.

For a square grid of width δ,

$$q\Big|_{\Gamma_E} = -\left[K_x\Big|_{\Gamma_E}\right]\left(H_E - H_c\right)\Big/\delta \tag{10}$$

where

$$K_x\Big|_{\Gamma_E} = \begin{cases} \left[\dfrac{1.486}{n}\,\bar{h}^{5/3}\right]_{\Gamma_E} \Big/ \left|\dfrac{H_E - H_c}{\delta\cos\theta}\right|^{1/2} \; ; & \bar{h} > 0 \\ 0 \; ; \; \bar{h} \leq 0 \text{ or } \left|H_E - H_c\right| < 10^{-3} \end{cases} \tag{11}$$

In Equation 11, h and n are both the average of the values at c and E, i.e. $h = (h_c + h_E)/2$ and $n = (n_c + n_E)/2$. Additionally, the denominator of K_x is checked such that K_x is set to zero if $|H_E - H_c|$ is less than a tolerance such as 10^{-3} ft.

The model advances in time by an explicit approach

$$\underset{\sim}{H}^{i+1} = \underset{\sim}{K}^{i}\,\underset{\sim}{H}^{i} \tag{12}$$

where the assumed input flood flows are added to the specified input nodes at each time step. After each time step, the conduction parameters of Eq. (11) are reevaluated, and the solution of Eq. (12) reinitiated. Using grid sizes with uniform lengths of one-half mile, time steps of size 3.6 sec were found satisfactory.

Figure 2 shows a flow chart for computation procedure. Verification of the 2-D model is given in Hromadka[2], Hromadka et al.[2], Hromadka and Durbin[3], and Hromadka and Lai[4]. Hromadka and DeVries[5] demonstrated the use of the two-dimensional model in the analysis of dam-break flood plains.

MATHEMATICAL DEVELOPMENT FOR ONE-DIMENSIONAL MODEL

By eliminating a directional component in Eq. (9), a one-dimensional formulation is developed which provides a good approximation of one-dimensional unsteady flow routing including backwater effects and subcritical/supercritical flow regimes.

INTERFACE MODEL (FLOODING SOURCE/SINK TERM)

To model flood flows exiting from and returning to a one-dimensional channel, an interface model is needed to couple the 1-D DHM and 2-D (topography) DHM. Figure 3 illustrates the mass conservation scheme assumed to represent the source/sink term of flows flooding/draining from the topographic model to the channel model.

INCLUSION OF CHANNEL CONSTRICTION EFFECTS

The main cause of many flood plain difficulties is the existence of channel constrictions due to bridges, undersized culverts, and other factors. By specifying a stage-discharge relationship at points within the channel system (or on the topography), constrictions are modeled efficiently in the DHM.

Some Results

In the current work on the DHM model the 1-D and 2-D DHM formulations are coupled through the interface model of the flooding source/sink term (due to channel overflows onto the topographic model). Using simple grid elements. Figure 4 shows a problem definition involving 160 grid elements for the topographic model and 3 channel systems. Included in the middle channel system is a junction. The channel drain towards culverts (located at the bottom of the domain) which have a limited capacity (e.g., road crossings). Figure 5 shows the channel inflow hydrographs and pertinent topographic data to indicate catchment divides. Figures 6, 7, 8, 9, and 10 show the flood plain extent at various model time values. Figure 11 shows the three channel outflow hydrographs which reflect the release of ponded waters due to culvert constrictions. Figure 12 shows the hydrographs at grid points 1 and 2 as flow escapes to the left of the domain. (For this application, zero flux is assumed on the right side of the domain, with critical depth assumed for the left side). Figures 13 and 14 show the maximum flood depths calculated in both plan and profile views, respectively.

The model results indicate that the current simple version of the DHM provides a considerable advance in floodplain determination over other simple methods currently available.

CONCLUSIONS

The DHM provides a very useful tool for hydrologists and hydraulic engineers who are involved in floodplain management or flood analysis. Through this new modeling approach, the analysis of flood control systems and development of methodology on how to best spend available dollars has been improved.

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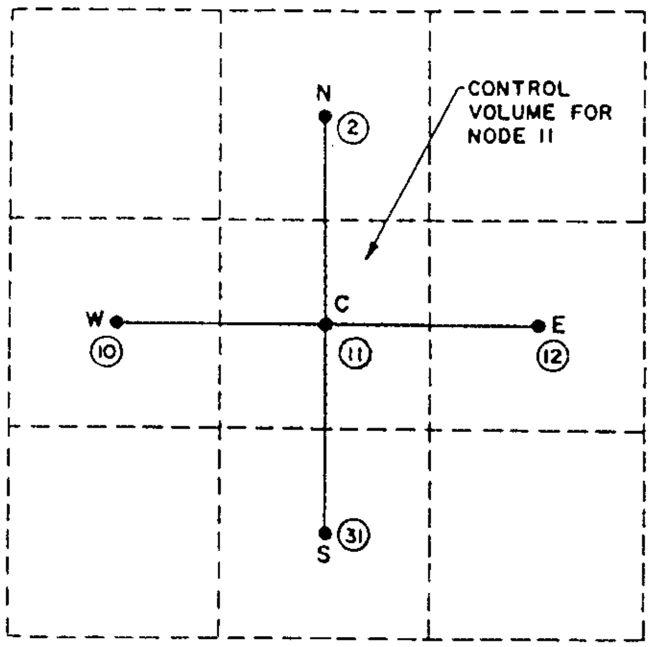

Fig. 1 Grid element nodal molecule

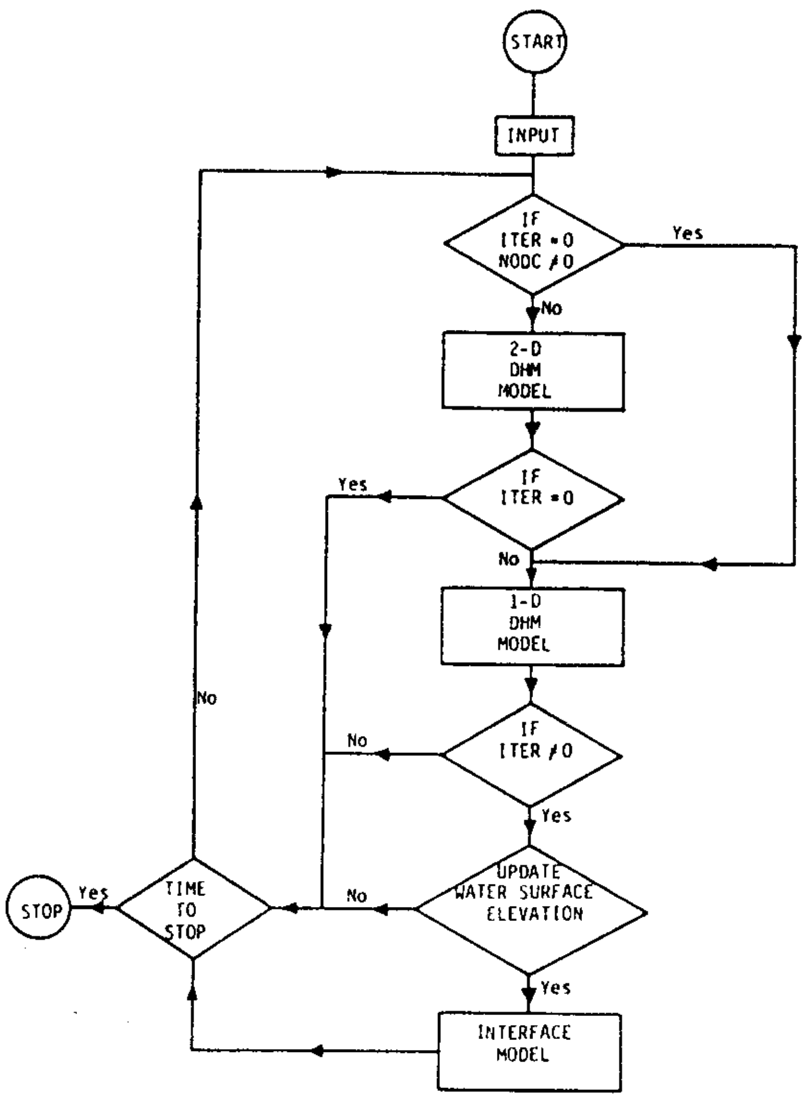

Fig. 2 Flow chart for DHM model

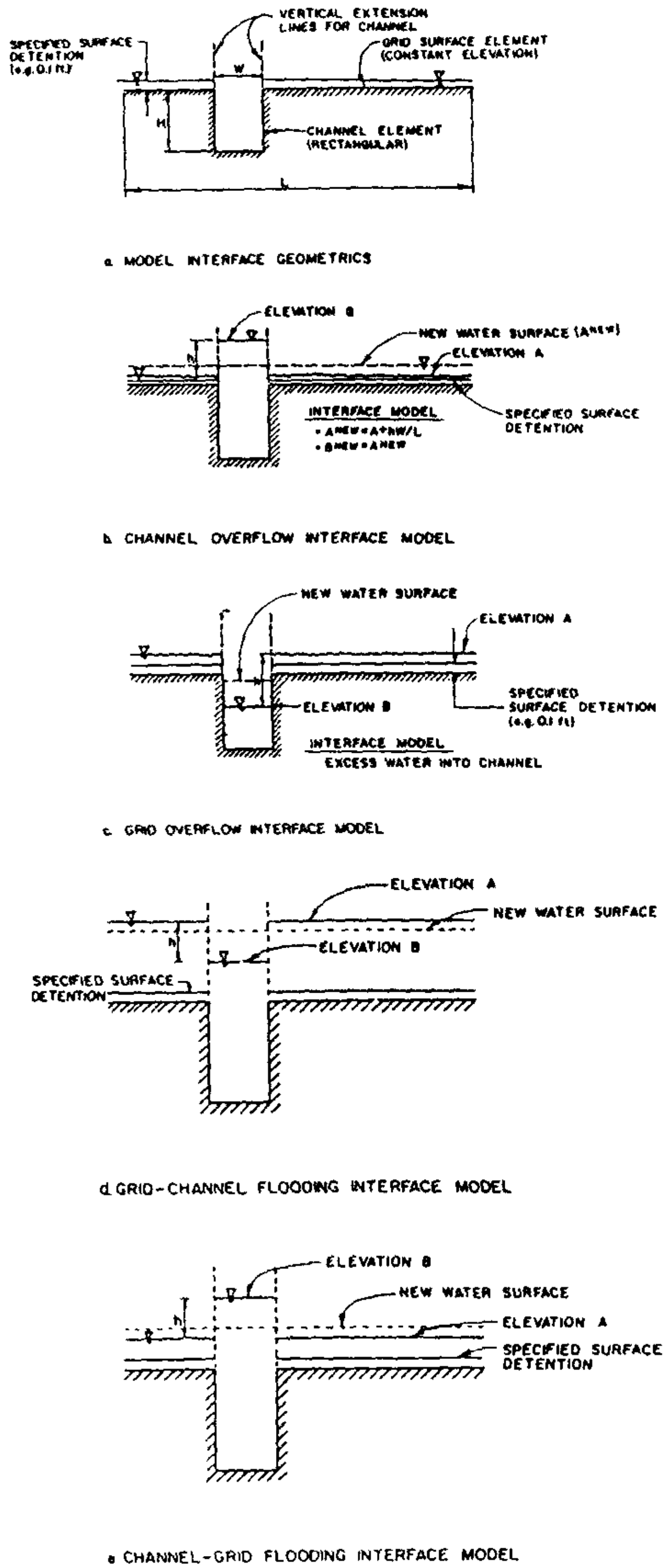

Fig. 3 DHM interface model

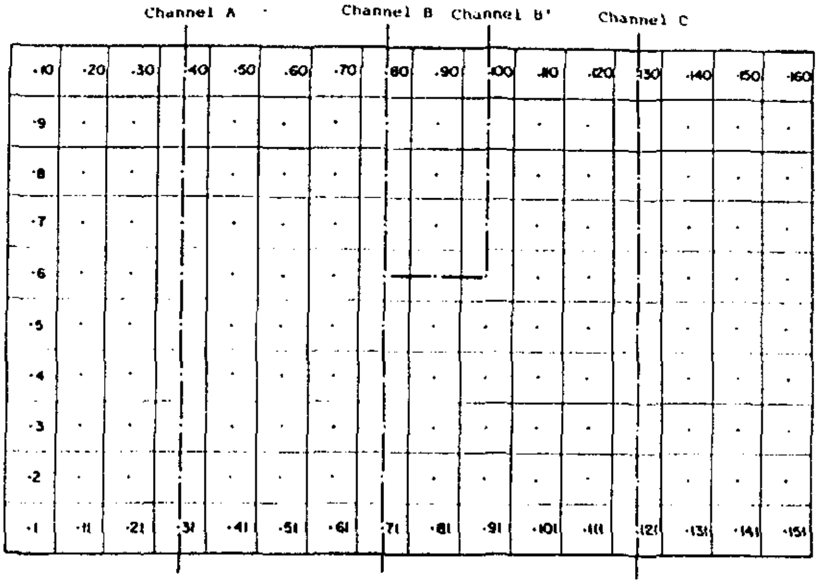

Fig. 4 DHM model discretization of a hypothetical watershed

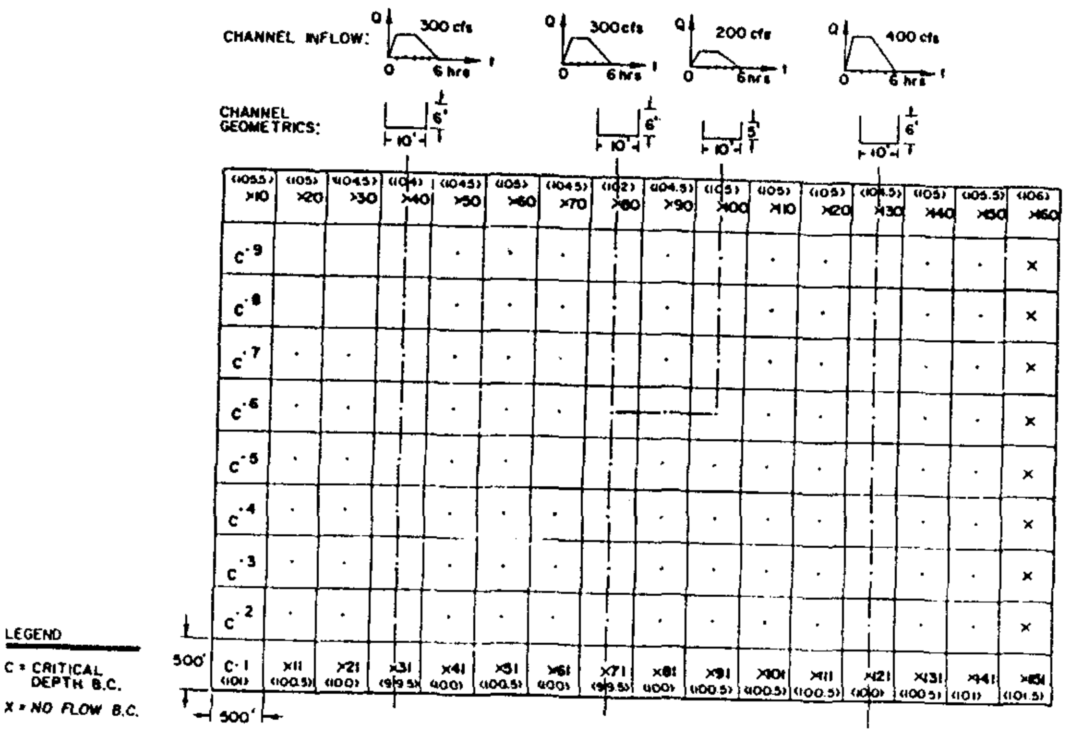

Fig. 5 Inflow and outflow boundary conditions for the hypothetical watershed model

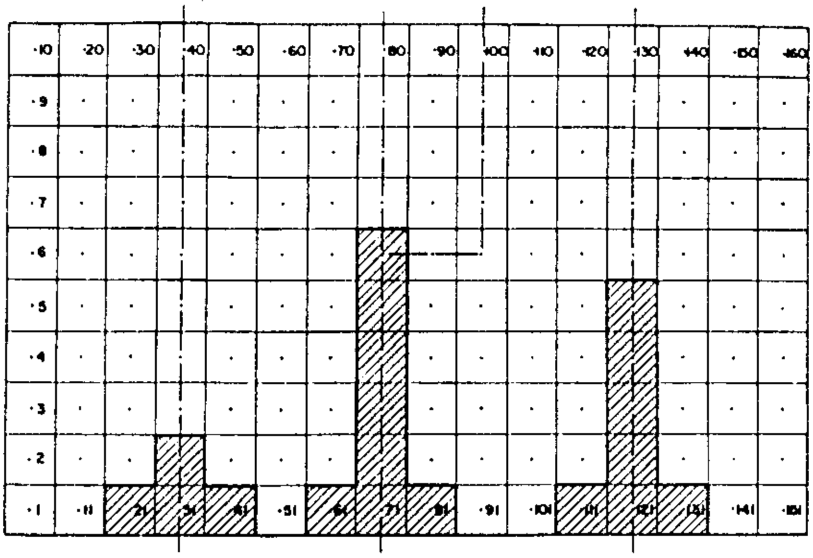

Fig. 6 DHM modelled floodplain at time = 1 hour

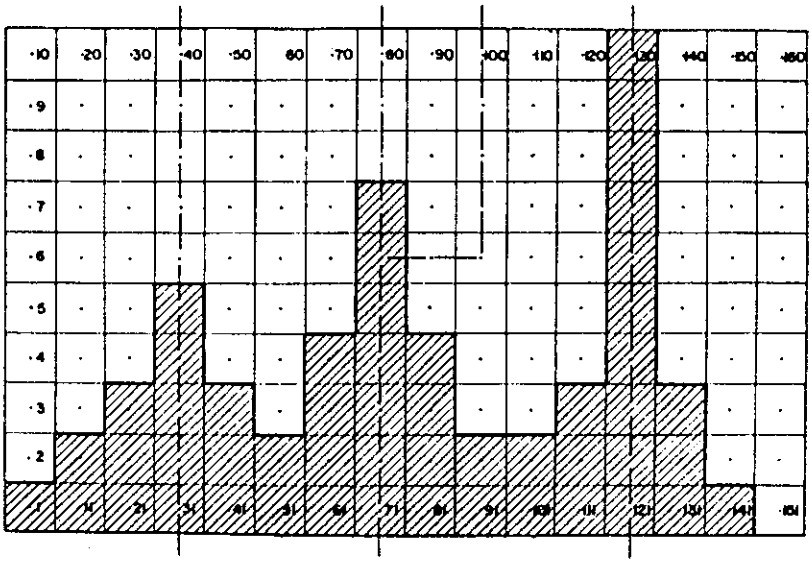

Fig. 7 DHM modelled floodplain at time = 3 hours

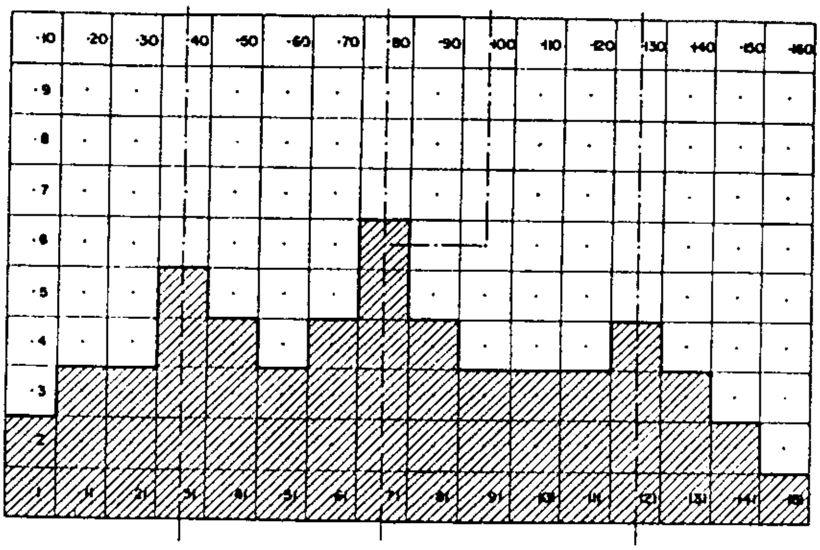

Fig. 8 DHM modelled floodplain at time = 5 hours

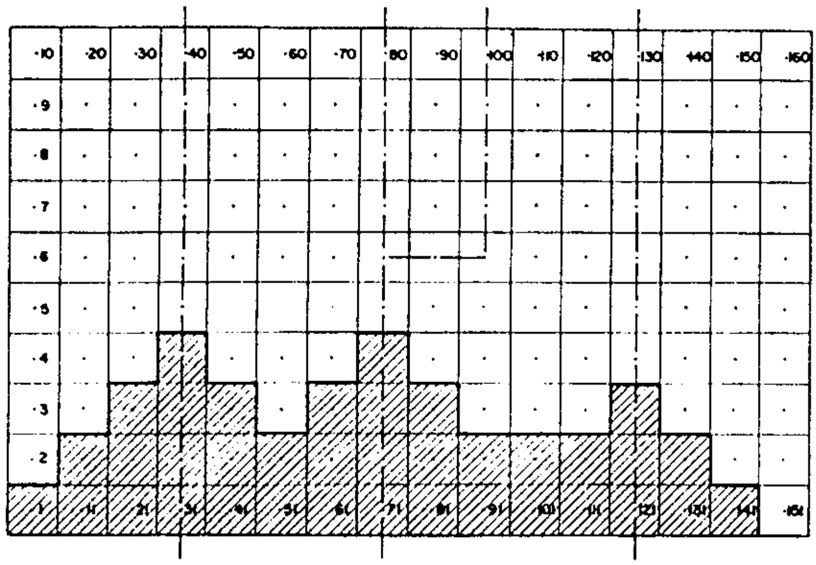

Fig. 9   DHM modelled floodplain at time = 7 hours

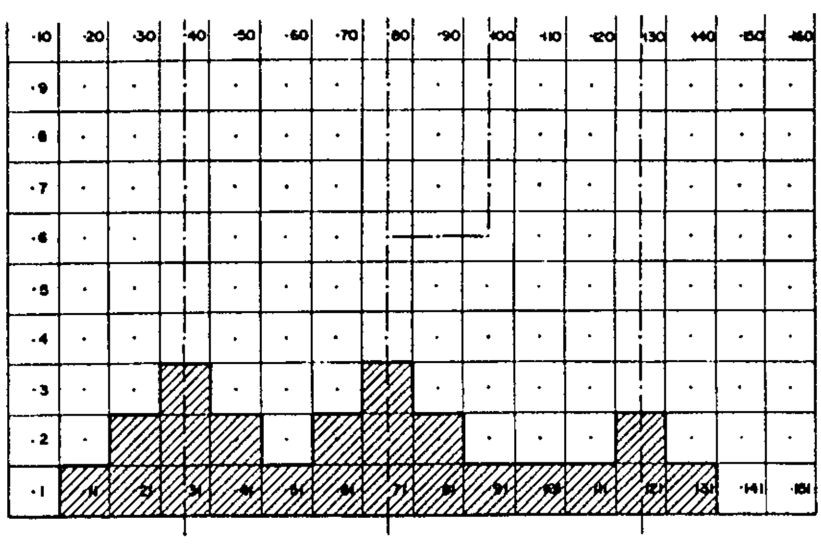

Fig. 10   DHM modelled floodplain at time = 10 hours

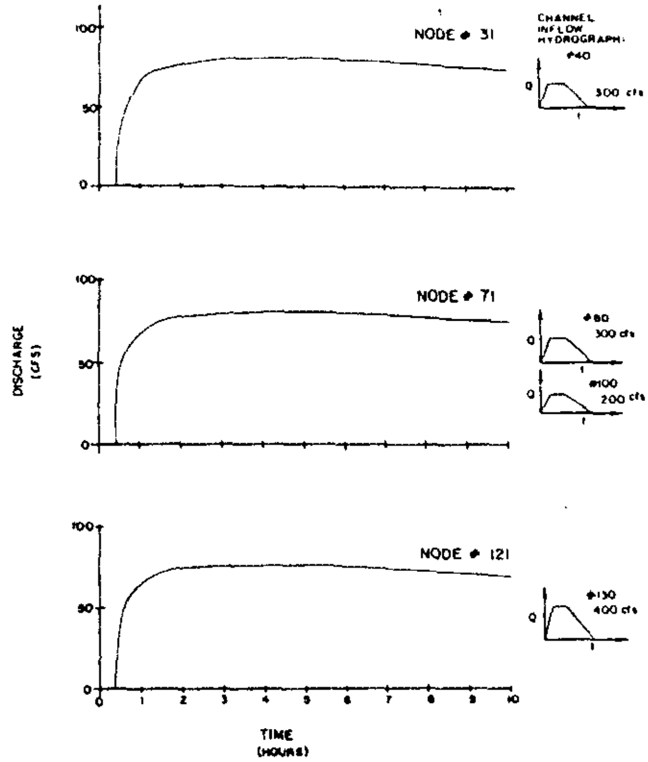

Fig. 11 Bridge flow hydrographs assumed outflow relation: (Q = 10d)

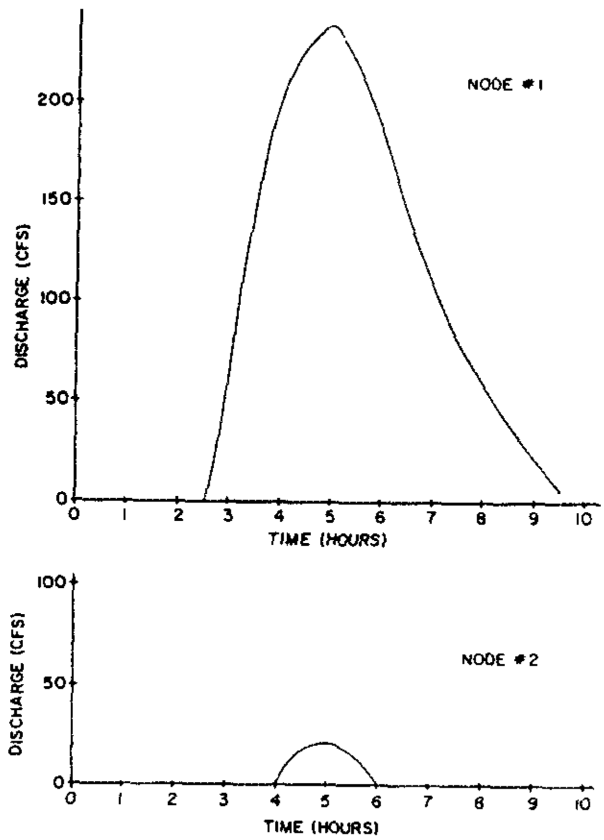

Fig. 12 Outflow hydrographs for floodplain based on critical depth conditions.

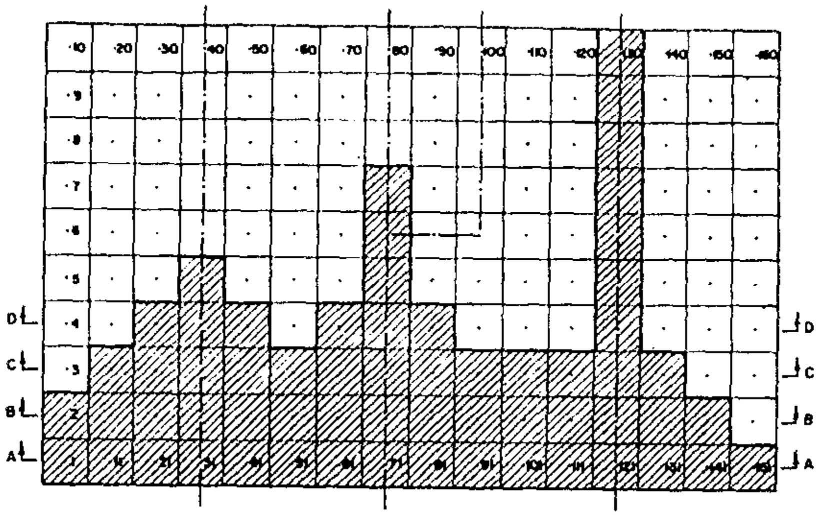

Fig. 13 Maximum extent of floodplain.

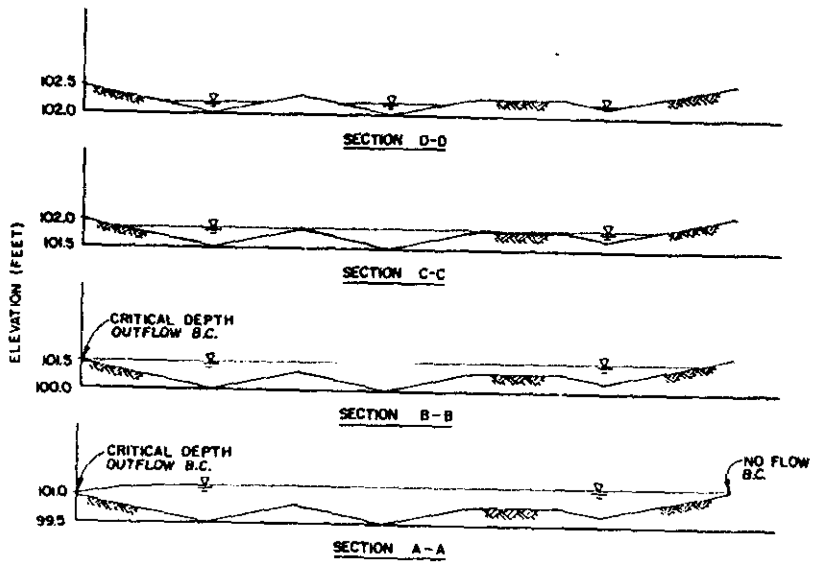

Fig. 14 Maximum water depth at various cross-sections.