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Linkage of a GIS to a Distributed Rainfall-Runoff Model

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Environmental modeling of natural phenomena is made difficult by characteristics such as spatial and temporal variability, dominating mechanisms that vary with environmental circumstances, uncertain factors, and scale effects. These effects are particularly inherent in distributed land surface, and near surface, rainfall-runoff modeling. GIS technologies offer powerful tools to deal with some of these problems. This chapter summarizes some experiences with the integration of GRASS (USACERL, 1988) and a distributed rainfall-runoff model. The system is simple to implement and is currently installed on a SUN workstation operating under the UNIX system.

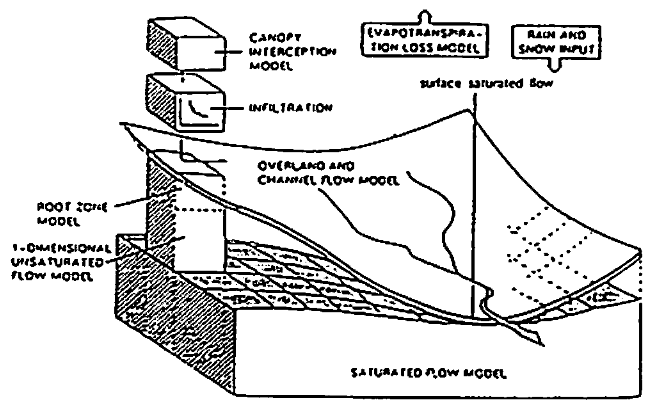

Figure 17-1: Description of the model structure.

MODEL DESCRIPTION

As part of a NASA-supported EOS (Earth Observation System) project (Kerr and Sorooshian, 1990), a physically based distributed model has been developed to study the dominant runoff production mechanisms under different environmental conditions and different spatial and temporal scales.

The model consists of several coupled modules, each describing a different hydrologic subprocess. Discretization of the horizontal land surface is done using a grid system of rectangular elements that correspond to the cells in the GIS. Vertical discretization of each soil column, with a cross section equal to the grid area, is done using layers to a user-specified depth. However, these are not stored as separate GIS layers due to memory constraints. The drainage network is superimposed along the edges of the grids (the river network becomes a series of straight line segments running along the grid edges). A schematic description of the model appears in Figure 17-1.

This model uses the finite difference method to solve a set of partial differential equations that characterize different hydrologic components. The following sequence of equations applies to the estimation of runoff from rainfall on an individual grid element and into a drainage network.

Rainfall input data are first processed through a "rainfall intensity module" and a "canopy interception module" to produce distributed "effective rainfall" on the soil surface. When the effective rainfall intensity is greater than the saturated hydraulic conductivity of the soil, a surface saturated zone in the soil is created. The infiltration rate is regulated by the Green–Ampt equation (Green and Ampt, 1911), and any infiltration excess results in overland flow. The 2D kinematic wave equation is used to simulate overland flow:

$$\frac{\partial d_0}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\sqrt{S_0}}{n} d_0^{5/3}\cos\alpha\right) + \frac{\partial}{\partial y}\left(\frac{\sqrt{S_0}}{n} d_0^{5/3}\cos\beta\right) = R - I - E \quad (17\text{-}1)$$

where

$d_0(x,y,t)$ = depth of overland flow (output)
t = time
x,y = horizontal coordinates (geometric parameters from DEM)
s_0 = soil surface slope (soil parameter)
$(\cos\alpha, \cos\beta, \cos\gamma)$ = direction vector of overland flow along the slope (parameter)
n = Manning coefficient of the soil surface (surface friction parameter)
I = infiltration rate (input from Green–Ampt equation)
R = effective rainfall intensity (input)
E = potential evaporation rate (input).

In the surface saturated zone, subsurface lateral flow is generated by the force of gravitation. It flows parallel to the surface slope, and a wetting front that separates the surface saturated part from the unsaturated zone moves downward into the unsaturated zone. The 2D governing equation for this process is:

$$k_s\left(z_0 - z_w\right)\left(\frac{\partial^2 z_w}{\partial x^2} + \frac{\partial^2 z_w}{\partial y^2}\right) + k_s\left(\frac{\partial z_0}{\partial x} - \frac{\partial z_w}{\partial x}\right)\left(\frac{\partial z_w}{\partial x}\right) + k_s\left(\frac{\partial z_0}{\partial y} - \frac{\partial z_w}{\partial y}\right)\left(\frac{\partial z_w}{\partial y}\right) + \left(\theta_s - \theta_w\right)\frac{\partial z_w}{\partial t} = I - T \qquad (17\text{-}2)$$

where

$z_w(x,y,t)$ = wetting front elevation (output)
z_0 = elevation of the soil surface (geometric parameter from DEM)
θ_s = saturated soil moisture content (soil parameter)
θ_w = soil moisture content ahead of the wetting front (input state variable)
T = transpiration rate through the roots (vegetation parameter) (Dickinson et al., 1986)
k_s = soil saturated hydraulic conductivity (soil parameter).

Stream flow in the river network is routed using the St. Venant equations:

$$\frac{\partial By}{\partial t} + \frac{\partial Q}{\partial x} = q_l \qquad (17\text{-}3)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} = gA\left(s_0 - s_f\right) - q_l\frac{Q}{A}$$

where

$y(x,t)$ = stream flow depth (output)
$Q(x,t)$ = stream flow discharge (output)
x = distance coordinate along the river from the upstream end
A = stream flow cross area (geometric parameter)
B = stream flow top width (geometric parameter)
q_l = total lateral inflow through a unit length of the bank [input from Eqs. (17-1), (17-2), and (17-5)]
g = gravitational acceleration (constant)
s_0 = river bed slope (geometric parameter)
s_f = friction slope (surface parameter)

If the effective rainfall intensity on a soil grid is small, then it becomes the flux boundary condition at the top of the soil column. The 1D Richard's equation is used to calculate the vertical moisture profile in the soil column:

$$C\frac{\partial \psi}{\partial t} = -\frac{\partial}{\partial z}\left[k\left(\frac{\partial \psi}{\partial z} + 1\right)\right] - T \qquad (17\text{-}4)$$

where

$\psi(z,t)$ = soil suction uniquely dependent on θ (Clapp and Hornberger, 1978) (output)
z = vertical coordinate with positive direction downward
$k(\theta)$ = unsaturated soil hydraulic conductivity (soil parameter)
$C(\theta)$ = soil specific moisture capacity (soil parameter).

Where the groundwater table is shallow, it plays an important role in runoff production. Groundwater flow is simulated using the 2D groundwater flow equation:

$$\frac{\partial}{\partial x}\left(k_s b\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_s b\frac{\partial h}{\partial y}\right) - T + W = S_y\frac{\partial h}{\partial t} \qquad (17\text{-}5)$$

where

$h(x,y,t)$ = hydraulic head of groundwater (output)
b = groundwater depth [equal to $(h - h_b)$, where h_b bedrock elevation]
S_y = specific yield [equal to $(\theta s - \theta)$, from Eq. (17-4)]
W = groundwater recharge intensity [input from Eq. (17-4)]

The model is programmed according to the flow chart in Figure 17-2 while employing the equations presented. Further explanation of several computational points follows:

1. The calculation area is usually chosen to be a watershed. GRASS is used to analyze the digital elevation map (DEM) to create all watershed boundaries and river networks within a region map based on the algorithms of Band (1989).
2. The calculation grid size is usually larger than the DEM resolution. Using the GRASS function for changing map resolution, the watershed boundary and

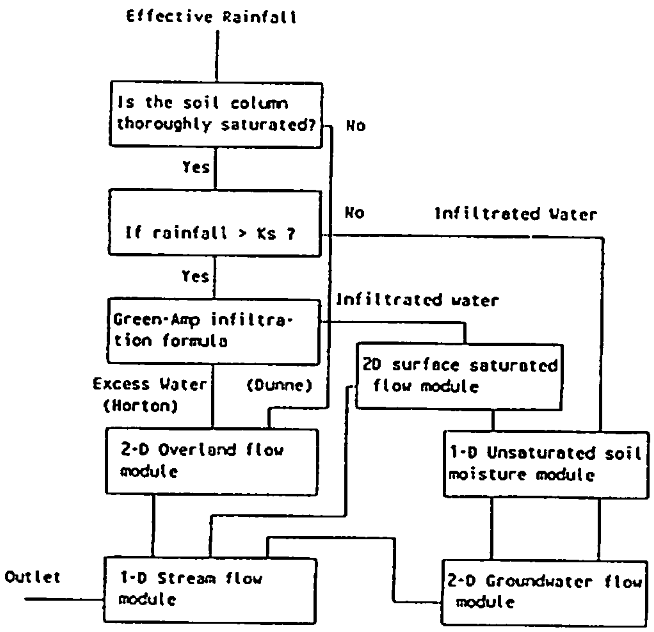

Figure 17-2: Flow chart of the model.

river network can be transformed to a series of straight line segments running along the grid sides so that they serve as boundaries for Equations (17-1), (17-2), and (17-5); the line segments corresponding to the river network collect the river inflows. While such a transformation changes the river length, the real river lengths calculated from the DEM are used when the river routing equations (17-3) are solved.

3. Geometric parameters such as s_0, $\cos\alpha$, $\cos\beta$, and $\cos\gamma$ (except those related to the river cross sections) can be calculated from the DEM using GRASS.
4. Soil parameters, vegetation parameters, and surface friction parameters can be determined at any grid element from soil, vegetation, and land use/cover maps using GRASS.
5. When numerically solving the equation set (17-1–17-5), some coupling is required to reflect the interactions between different processes. The coupling relationships in a soil column are as follows. When the wetting front of the surface saturated zone moves downward or as the groundwater table rises, the water from the saturated zones will fill the unsaturated region ahead of the front. The soil moisture content varies along the unsaturated soil moisture profile calculated by Equation (17-4). When the soil moisture profile is calculated, the depth of the unsaturated soil column is varied with the rising or falling of the groundwater table; therefore the lower boundary condition is set to $\psi = 0$ at the elevation of the groundwater table.
6. After the new soil moisture profile is created, a volume balance is conducted. The total volume difference between the successive profiles is defined as the groundwater recharge, W.

CASE STUDY

A simple example is presented here to illustrate how the integrated model-GIS system works: the hydrologic response of the Lucky Hills-104 semiarid watershed (4.4 ha) is simulated for a storm event that occurred on Aug. 1, 1974. The watershed is located in the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona; extensive rainfall and runoff data have been collected there on an ongoing basis as part of a long-term research program (Renard, 1970). A detailed 15 m x 15 m DEM database was obtained photogrammetrically using low-level aerial photography. Soil hydraulic information was obtained through field surveys at a number of points in the subwatershed (Goodrich, 1990). A planimetric illustration of the watershed and associated raingages is presented in Figure 17-3; a more detailed description of the watersheds can be obtained in Kincaid et al. (1966). In this watershed, the groundwater table is remote from the surface topography. Therefore, model components related to surfacegroundwater interaction are not exercised in this case study. Basins where groundwater interactions are significant will be examined in the future. The case study is used in the following section to illustrate linkage between the model and the GRASS GIS.

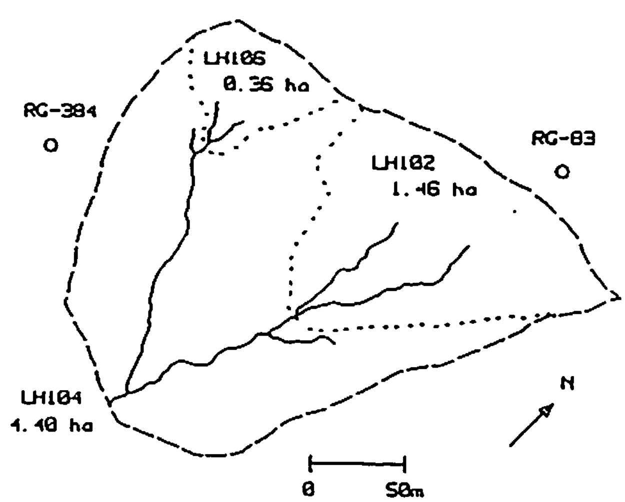

Figure 17-3: Lucky Hills-104 watershed.

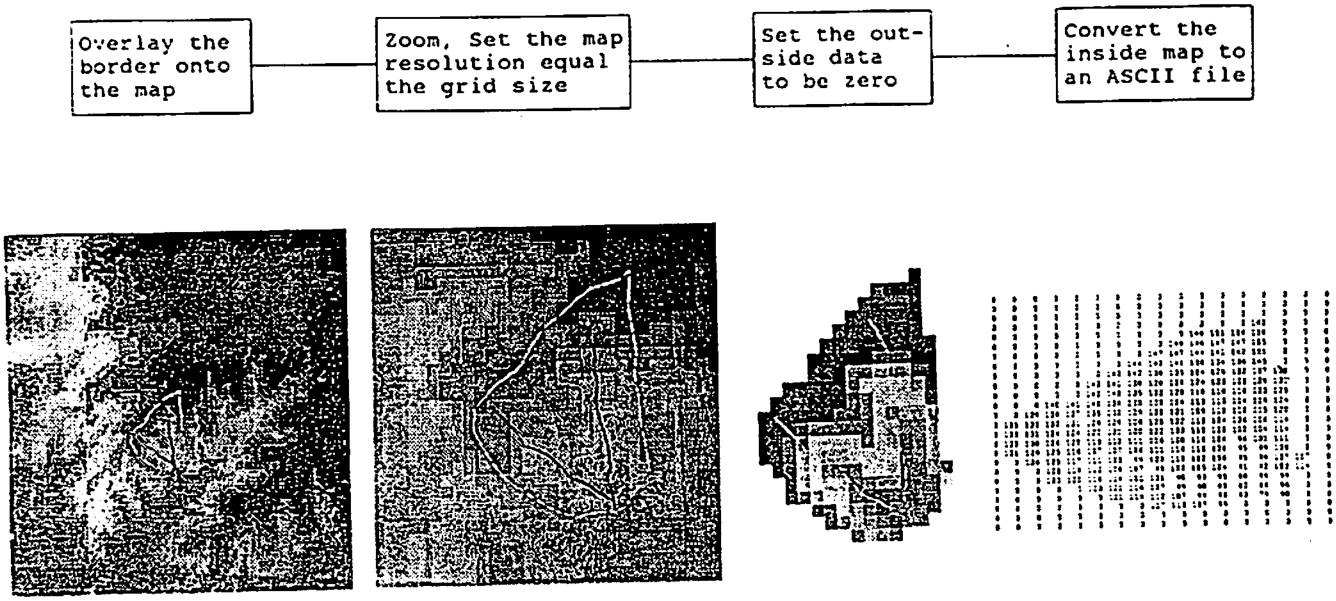

Figure 17-4: Watershed DEM data extraction.

THE MODEL-GIS SYSTEM

The model employs several idealized two-dimensional hydrological processes and their interactions to simulate a complex three-dimensional natural hydrological phenomenon. Almost all the input data, output results and parameters employed by the model are distributed on two-dimensional surfaces; many also vary with time. The primary linkage between the model and the GIS involves initial drainage basin characterization and handling and display of distributed model input and output. The use of a GIS greatly facilitates the data management and visualization tasks. In order to take full advantage of a GIS, some commonly-used functions were created: GRASS commands were used here. In addition, UNIX macros were formulated to link GRASS with the model to create an integrated system. When the model is run, GRASS is simultaneously initiated to provide the functions described in the following sections.

Ease of model setup and modification

A large amount of data describing the spatial distribution patterns of the input data and watershed parameters must be input into the model in the form of numerical matrices. The tedious nature of this work is especially apparent when unknown or uncertain parameters must be adjusted many times in order to calibrate the model. To simplify and facilitate this process, several GRASS-GIS commands are programmed to extract data required by the model from digital maps. The steps used in our illustrative example are:

1. Data retrieval: Given a watershed boundary and DEM data, extract the within-boundary data and transform it into a numerical matrix. The extraction of digital elevation data for Lucky Hills 104 is illustrated in Figure 17-4.
2. Data editing: Altering the map values (which represent certain categories) in a specified area, while keeping the remaining values in other areas unchanged. This useful macro can be realized through several GRASS procedures:
   a. Using the mouse, outline the boundary of a map area to be edited and record the boundary as a vector file.
   b. Convert the vector file to two special cell maps, map1: inside = assigned value, outside = 0; map2: inside = 0, outside = 1.
   c. Perform map operation: New map = (Original map) * map2 + map1.

Visualization of model processes

The use of GRASS-GIS in conjunction with other data visualization packages offers a simple way to monitor the modeling procedure; sequences of frames that depict the distributed dynamics of the modeled process can be easily constructed and viewed. Key physical variables and distributed physical fields can be readily displayed. This facilitates a better understanding of the hydrologic process and enables rapid error detection and correction. The basin outflow hydrographs at the outlet of Lucky Hills-104 and two nested subcatchments are illustrated in Figure 17-5. A schematic of the distributed overland flow depths (cm) at several times during the rainfall-runoff simulation event are illustrated in Figure 17-6.

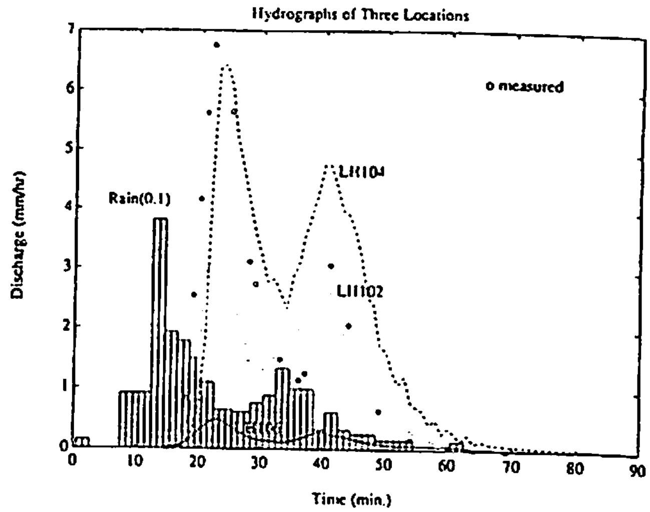

Figure 17-5: Simulated catchment and subcatchment hydrographs.

Creation of maps at larger spatial scales

Map data and remotely sensed data are available at various different spatial resolutions. To combine data from different sources, the ability to reformulate model inputs and outputs at various scales is required. When rescaling from smaller to larger pixel sizes, issues regarding the loss of information by averaging must be addressed. For example, the brightness information in a 4 m × 4 m pixel may

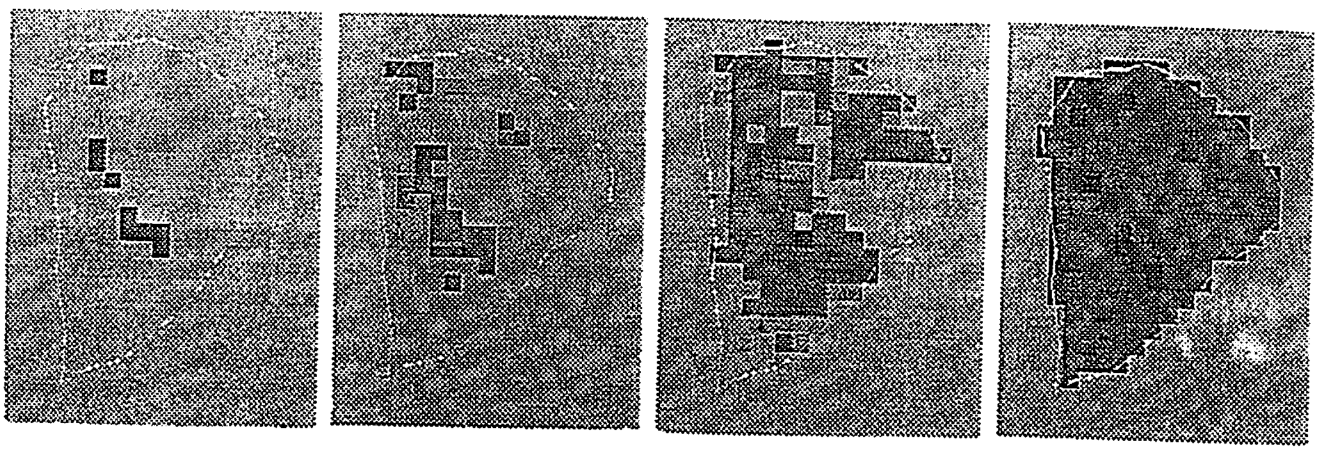

Figure 17-6: Variation of overland flow intensities.

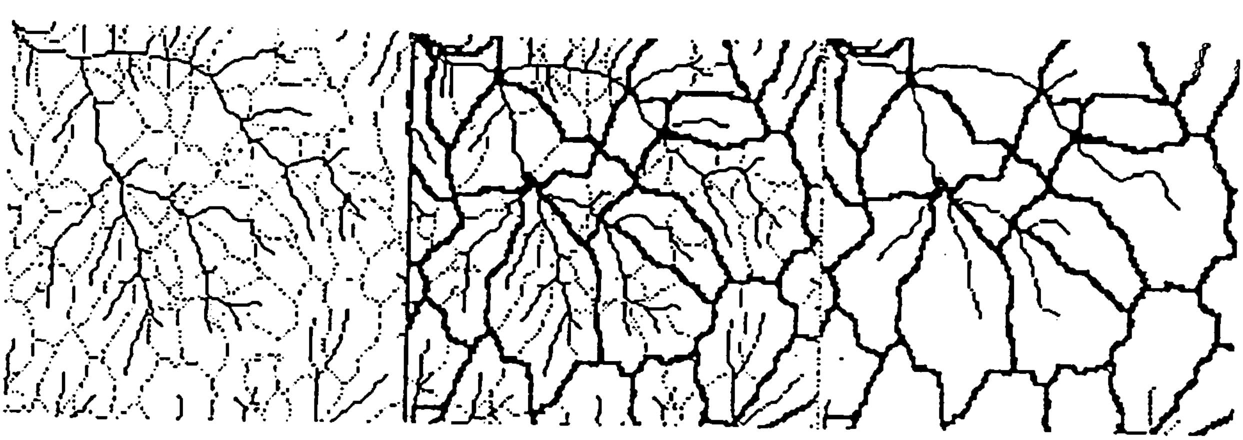

Figure 17-7: Combination of subcatchments via stream order reduction.

reflect some combination other than simple averaging of the information contained in the corresponding 16 1 m × 1 m pixels. Simple GRASS filters can be used to customize the method of grid averaging. In addition, GRASS can perform very complex user-defined map operations to generate composite maps. For example, Figure 17-7 illustrates the use of a GRASS macro to combine smaller subcatchments into larger subcatchments via a stream order reduction methodology. This facility is very useful for the study of issues related to scaling in hydrologic modeling.

CONCLUSIONS

Preliminary results indicate that the physically based distributed model described here can simulate the spatial variability of the rainfall-runoff phenomenon, although additional validation must be conducted. In the case study presented, parameters used by other models (Woolhiser et al., 1990) were applied without calibration. The simulated hydrograph at the Lucky Hills-104 watershed was found generally to match observed data. The model also provided a distributed dynamic description of the hydrologic response occurring in this watershed: processes such as soil moisture redistribution, runoff generation and diminution, stream flow variation, and so on were simulated. However, model accuracy is obviously limited by the requirement for large amounts of data of good quality. Validation of spatially distributed hydrologic response data (i.e., grid overland flow depth or average grid infiltration rates) is extremely difficult and costly and may not be realistic. If such data are not available, the model-GIS system discussed may be more properly used as an investigative tool to target additional data collection and identification of model components requiring improvement. Employed in this fashion, GIS technologies can provide powerful tools that can enhance the efficiency and effectiveness of numerical environmental models and simplify the investigation of the behavior of spatially distributed phenomena.

This paper has described some of our experience with the integration of GRASS (GIS) and a distributed rainfall-runoff model. The resulting system greatly facilitates visualization of the data, ease of model setup and analysis of model outputs. An important application of the system is the study of model-scale issues in surface hydrology. The experience acquired during our present research clearly illustrates the power and time-saving capabilities that GIS technologies can provide.

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