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# Flood Forecasting Reaches New Potential

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Natural disasters caused by floods challenge scientists to forecast the magnitude and timing of peak flood discharges more accurately. With recent advances in Geographic Information Systems (GIS) and computer technology, scientists have developed large-scale surface runoff models to improve flood forecasting.

Recent advances have produced two-dimensional surface runoff models with direct access to large raster-based GIS data sets. Julién and Saghafian [1991] developed the first version of the model CASC2D at Colorado State University to simulate surface runoff from flash floods caused by intense thunderstorms moving across watershed areas. The detailed components of CASC2D include the Green and Ampt infiltration equation, the diffusive wave approximation of the Saint-Venant equation, and the interaction between overland and channel flow.

A wealth of raster-based GIS data files at 30 m resolution describe topography from digital elevation models, soil infiltration parameters from Soil Conservation Service soil classification maps, and interception storage and surface roughness parameters defined from land-use maps.

With its unique color capabilities, CASC2D displays the spatial and temporal variability of rainfall, infiltrated depth, and surface flow depth, as shown in Julién et al. [1995]. CASC2D calculates both the infiltration depth and the surface flow depth on each pixel at each time step. The flow hydrograph can be plotted for any selected point on the watershed.

Julién et al. [1995] demonstrated the capabilities of CASC2D for modeling flash floods from localized storms in semi-arid areas like Macks Creek, Idaho. Doe et al. [1996] linked raster-based GIS data files with the model CASC2D in semi-arid areas like Taylor Arroyo, Colorado, for detailed spatial and temporal analyses of watershed impact of various land management scenarios. The model has been calibrated and independently verified to accurately simulate watershed response to moving rainstorms on watersheds with spatially varied infiltration in humid areas such as Goodwin Creek and Hickahala-Senatobia watersheds in Mississippi.

Molnár [1997] determined the effects of grid size, ranging from 30 m to 1 km, in CASC2D surface runoff calculations. CASC2D was applied to the 21 km<sup>2</sup> Goodwin Creek watershed and the larger, 540 km<sup>2</sup> Hickahala watershed in northern Mississippi. The challenge of performing surface runoff calculations on large watersheds (exceeding 100 km<sup>2</sup>) is indeed daunting, but CASC2D simulations are now possible with half-a-million pixels available.

The elevation and land use maps (Figures 1a and 1b respectively) define the state variables of the Hickahala-Senatobia watershed. The flow depth maps after 2.5 and 12 hours (Figures 2a and 2b respectively) were generated from the model CASC2D. Conditions for this simulation include a constant rainfall intensity of 25.4 mm/hr over nearly impervious soils, a rainfall duration of five hours, and a calculation time step of one second. For the first time, a computer model can calculate surface runoff in a complex watershed represented by a total of 548,000 pixels.

## Analysis of Spatial and Temporal Variability

Four parameters play a dominant role in the analysis of spatial and temporal variability of surface parameters, infiltration characteristics, and rainfall precipitation: rainfall duration,  $t_r$ ; time to equilibrium,  $t_e$ ; average rainfall intensity,  $I$ ; and average saturated hydraulic conductivity,  $K$ . For complex watersheds analyzed with CASC2D an algorithm for calculating the time to equilibrium is defined from spatially varied watershed characteristics and excess rainfall intensity. The wave travel time from the hydraulically most remote point to the outlet is calculated for both overland flow and channel flow. The effects of spatial and temporal variability are measured by the relative sensitivity parameter  $R$ , defined as the ratio of the variance of the outflow hydrograph to the variance of the incoming rainfall intensity. For impervious areas, the variability in one-dimensional surface runoff is inversely proportional to the ratio  $t_r/t_e$ . For runoff on near-impervious two-dimensional watersheds, the variability in surface runoff also decreases with  $t_r/t_e$ . Similarity in surface runoff generated on heterogeneous soils shows that runoff variability decreases as  $t_r/t_e$  increases unless the saturated rainfall intensity approaches hydraulic conductivity. In highly pervious watersheds, the steady state discharge depends on the spatial distribution of hydraulic conductivity. Saghafian et al. [1995] found that lumped values of saturated hydraulic conductivity typically underestimate the peak discharge and runoff volume. For highly pervious areas, runoff dominates surface flows and the variability in surface flows increases with both  $t_r/t_e$  and  $K/I$ . The time variability of rainfall also affects surface runoff. The rainfall sampling resolution  $t$  is also important in that the runoff sensitivity asymptotically reaches  $\text{func}\{R_s \sim 5\sqrt{\delta t'/t_e}\}$  when  $t_r \gg t_e$ .

## Rainfall Simulations from Radar Data

The hydrologic model CASC2D has been coupled with the CSU-CHILL polarized dual-Doppler radar in Greeley, Colorado. The dual polarization capabilities of the radar improve the accuracy of measured rainfall rates. Ogden and Julián [1994] showed that reasonable runoff simulations can be obtained with rainfall rates detected by radar at 1 km resolution.

In addition to accurately measuring precipitation, radars offer tremendous capabilities in tracking the motion of severe thunderstorms, which can increased peak discharges when moving in the direction of drainage. The effect of storm motion on surface runoff hydrographs has been quantified with radar data and two-dimensional CASC2D runoff simulations. Specifically, the results in terms of dimensionless hydrologic parameters relate to the storm speed parameter  $U t_e / L_p$  where  $U$  is the storm speed,  $t_e$  is the time to equilibrium, and  $L_p$  is the runoff length. The maximum runoff peak is obtained when  $0.5 < U t_e / L_p < 1$ .

## Upland Erosion Simulations

GIS-GRASS raster maps have been used to analyze upland erosion, which varies spatially with rainfall, soil and land use characteristics, runoff length, and runoff slope. Grid resolution has a direct effect on erosion rates, as calculations using the Universal Soil Loss Equation (USLE) have demonstrated. For modeling upland erosion losses from single events [Johnson et al., 1997], the Kilinc-Richardson equation has been incorporated into CASC2D to compute the sediment transport capacity from one grid cell to the next. The upland erosion algorithm routes three sand, silt, and clay grain sizes from suspension, from previous deposition, and from the parent soil material. This calculation allows sediment to be deposited and then transported again without overestimating the erosion taking place on the soil surface. Once the estimated quantity of sediment reaches the receiving grid cell, the algorithm determines how much remains in suspension and how much is actually deposited on the receiving grid cell. This single event upland erosion algorithm has been tested by Johnson [1997] on a farm test plot and the Goodwin Creek watershed in Mississippi. These studies indicate that the algorithm works best at the watershed scale, as the micro topography of the test plot scale requires very fine pixels. For the Goodwin Creek watershed, the upland erosion routine computed sediment yield within  $\pm 20\%$  of that measured from sub-watersheds where upland erosion predominates. Using the CASC2D model, the design engineer can evaluate the impact of sub-watershed changes on the downstream channel system by analyzing the change in water and sediment yield. For example, CASC2D can be used to compute the net effect of timber harvesting in a sub-watershed on the water and sediment yield.

In the event that no net increase in flow discharge is desirable, an engineer can use CASC2D to perform a sensitivity analysis to select watershed management alternatives. By recognizing the fluvial geomorphic aspects of the existing channel system, one could determine the degree of change that a watershed could sustain without adverse consequences. In urban areas, evaluation of the sub-watersheds could be conducted to estimate increases in surface runoff and sediment yield. Mitigating alternatives could be developed in advance to minimize adverse impacts to the downstream receiving channels. Finally, the parent model FLO2D described by O'Brien et al. [1993] simulates clear-water flood hazards and estimates the route of mud and debris flows on alluvial fans and urban floodplains. CAD graphics enhances interactive modeling with predicted, time-sequenced flood depths, which alert managers to flood hazards.

## Acknowledgments

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## Figures

Fig. 1. a) Elevation Map of the Hickahala-Senatobia Watershed; b) Land Use Map of the Hickahala-Senatobia Watershed.

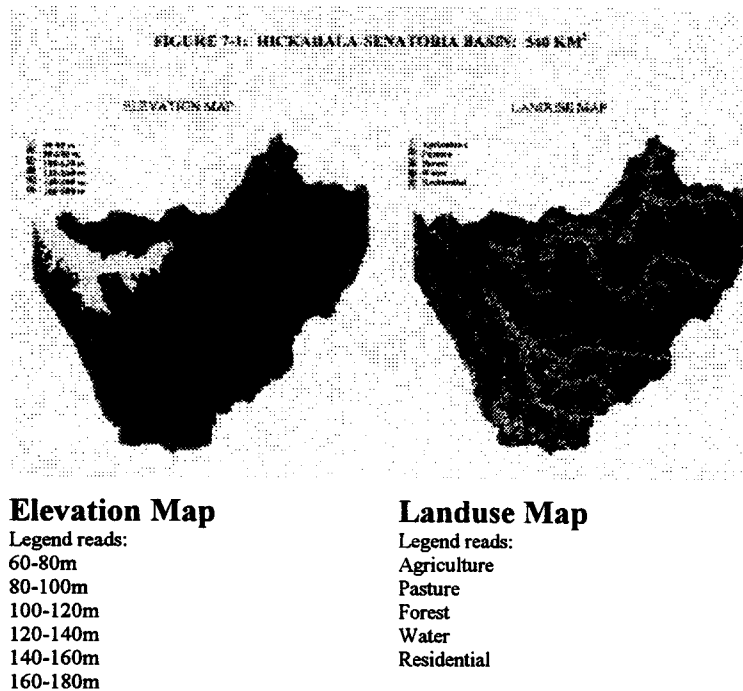


Fig. 2. a) CASC-2D Rainfall-Runoff Simulation on Hickahala-Senatobia Watershed, after 2.5 hours. b) CASC-2D Rainfall-Runoff Simulation on Hickahala-Senatobia Watershed, after 12 hours.

