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LAND-USE IMPACT ON WATERSHED RESPONSE: THE INTEGRATION OF TWO-DIMENSIONAL HYDROLOGICAL MODELLING AND GEOGRAPHICAL INFORMATION SYSTEMS

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ABSTRACT

The integration of a two-dimensional, raster-based rainfall–runoff model, CASC2D, with a raster geographical information system (GIS), GRASS, offers enhanced capabilities for analysing the hydrological impact under a variety of land management scenarios. The spatially varied components of the watershed, such as slope, soil texture, surface roughness and land-use disturbance, were characterized in GRASS at a user-specified grid cell resolution for input into the CASC2D model. CASC2D is a raster-based, single-event rainfall–runoff model that divides the watershed into grid cell elements and simulates the hydrological processes of infiltration, overland flow and channel flow in response to distributed rainfall precipitation. The five-step integration of CASC2D and GRASS demonstrates the potential for analysing spatially and temporally varied hydrological processes within a 50 square mile semi-arid watershed. By defining possible land-use disturbance scenarios for the watershed, a variety of rainfall–runoff events were simulated to determine the changes in watershed response under varying disturbance and rainfall conditions. Additionally, spatially distributed infiltration outputs derived from the simulations were analysed in GRASS to determine the variability of hydrological change within the watershed. Grid cell computational capabilities in GRASS allow the user to combine the scenario simulation outputs with other distributed watershed parameters to develop complex maps depicting potential areas of hydrological sensitivity. This GIS–hydrological model integration provides valuable spatial information to researchers and managers concerned with the study and effects of land-use on hydrological response.

KEY WORDS hydrology; rainfall–runoff models; watershed responses; geographical information systems

INTRODUCTON

The analysis of watershed response during rainfall–runoff events can be greatly enhanced by the integrated use of geographic information system (GIS) technology with physically based hydrological models. The advantages and disadvantages of using a GIS with hydrological modelling have been summarized by DeVantier and Feldman (1993). Successful applications of such integration were demonstrated by Ross and Tara (1993), who used this approach for the analysis of reclaimed mine site land use. An integrated GIS–modelling approach is particularly useful for land managers who are concerned with the range of effects caused by varying types and intensities of land-use within a watershed. The simulation of multiple

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land-use scenarios in the GIS–modelling environment can provide valuable spatial information to land managers and assist them with the implementation of sound land-use management practices.

In this study, the Geographic Resources Analysis Support System (GRASS), a raster-based GIS, is integrated with a two-dimensional, raster-based rainfall–runoff model, CASC2D, to investigate potential watershed impacts. The focus of this paper is to describe the general methodology used and to illustrate its utility for analysing spatially and temporally varied hydrological processes in a watershed during rainfall–runoff events. The emphasis is on the benefits brought by merging a raster-based GIS and hydrological model. In this respect, the substance of this analysis is not specific to GRASS and CASC2D; equivalent results should be obtained with comparable raster-based GISs and hydrological models. In a demonstration study, this integrated approach investigates land-use impacts on a 50-square mile, semi-arid watershed, the Taylor Arroyo, in south-eastern Colorado. The particular land-use impacts evaluated were disturbances caused by US Army tracked vehicle manoeuvers across the watershed.

WATERSHED DESCRIPTION AND RAINFALL CHARACTERISTICS

The Taylor Arroyo watershed encompasses a 50-square mile area of semi-arid grasslands and uplands in south-eastern Colorado. The baseline hydrology of the watershed has been studied and documented by von Guerard *et al.* (1987;1993). Their studies focused on the collection and analysis of rainfall and streamflow data as well as water quality parameters. The watershed is drained by a complex network of ephemeral streams or arroyos. Two principal arroyos drain the watershed and converge approximately 3 miles above the watershed outlet before entrenching into a deep rock canyon. Channel cross-sections vary greatly, but can be as deep as 3 m and as wide as 25 m. The arroyos are further characterized by steep banks of alluvium subject to downslope erosion. Rainfall events are infrequent and result primarily from intense convective thunderstorms in the summer. The dominant hydrological processes within the watershed are infiltration and channel flow. Infiltration is controlled primarily by the antecedent soil moisture conditions and the hydraulic properties of the surface layer. Subsurface flow from singular rainfall events is negligible. Channel flow is controlled primarily by the density of channel networks and surface runoff immediately adjacent to the channels.

A system of nine automated rain gauges and one stream gauge near the outlet is operated by the US Geological Survey (USGS). They provided distributed rainfall data and stream discharge data for this demonstration. These data were collected for a thunderstorm event occurring on 9 August 1987, which represented the largest recorded runoff event for the water year. The rainfall data used for the model calibration were recorded at 5 min intervals for a duration of 3 h. Simulations for the watershed were performed in CASC2D using this spatially distributed event as an undisturbed calibration example to determine how well the model represented the watershed and its hydrological response. Both the volumetric relationships for inflow–outflow and the peak discharge were simulated accurately (Doe, 1992).

Additional rainfall data were derived from historical precipitation–frequency maps for the south-eastern region of Colorado (Miller *et al.*, 1973). Rainfall data from these maps were used to determine representative storms of constant rainfall intensity for the 5 yr, 3 h event (2.0 equivalent inches of depth) and the 10 yr, 1 h event (1.9 equivalent inches of depth). These constant rainfall events provided standard storms to examine the effects of non-uniform surface characteristics on the spatial and temporal response's distribution of surface runoff on the watershed.

BRIEF DESCRIPTION OF CASC2D

CASC2D is a distributed, single-event, rainfall–runoff model. The model is fully documented in Julien and Saghafian (1991) and was initially developed as a research tool for analysing the spatial and temporal variations of watershed response. Since its development CASC2D has been applied to several watersheds for hydrological analysis. Saghafian (1992) calibrated and validated early versions of the model on a small, semi-arid watershed, Mack's Creek in Idaho, to examine the hydrological response due to spatially varied infiltration. Ogden and Julien (1993; 1994) used weather radar data with the model to test runoff sensitivity on both Mack's Creek and the Taylor Arroyo watersheds to temporally and spatially varied rainfall precipitation. Johnson *et al.* (1993) independently calibrated and tested CASC2D with observed data from five rainfall events on a small watershed in Mississippi. They reported that CASC2D performed well for these storm events, particularly with regard to the shape of the runoff hydrograph and peak flow computations. In selecting the CASC2D model for application to the Taylor Arroyo watershed, several factors were considered: (a) its ability to replicate the dominant hydrological processes found in the watershed, particularly infiltration and surface runoff adjacent to channels; (b) the capability to handle spatial and temporal variability; and (c) its compatibility with spatial data and raster GISs.

The primary features of CASC2D include the Green and Ampt method for infiltration, a two-dimensional, explicit solution of the diffusive wave form of the de St. Venant equations for overland flow, and a one-dimensional, explicit solution of the diffusive wave formulation for channel routing. Three hydraulic parameters (saturated hydraulic conductivity, capillary pressure head at the wetting front and soil moisture deficit) are required to solve the Green and Ampt equation. These parameters were determined from infiltrometer tests in the field and compared with the classifications of Rawls *et al.* (1983). The model also contains provisions to account for interception and detention storage, but these were not used in the simulations. To calculate surface runoff the model solves the two-dimensional equations of continuity and momentum which describe gradually varied overland flow. Resistance to flow is described by Manning's equation. Finite-width channel flow routing is performed in a similar fashion, but in only one direction along the channel path. The overland flow and channel flow are fully coupled to allow lateral inflows and outflows along the channel lengths.

The physical watershed domain in CASC2D is characterized by square (raster) grid cells. Raster data files for elevation, soil texture and surface roughness must be prepared. Although spatial variability is allowed from one grid cell to the next, each cell is represented as a homogeneous unit. The channel network is delineated in a file indicating the network connectivity and the physical characteristics of the various channel segments. The size of the surface feature files and channel network file is largely dictated by the user-selected grid cell resolution. At the selected grid cell size the channels were at a sub-grid cell scale, with the immediate floodplain composing the remainder of each channel cell in the file. In such a case the surface water depth accumulated over the floodplain portion of the cell is routed into the incised sub-grid cell size channel via a weir-type equation.

Uniform or spatially distributed rainfall data may be input to the model. For spatially distributed rainfall data the inverse distance squared algorithm is used to distribute the rainfall across the entire watershed. Rainfall–runoff simulation is performed for each grid cell at a user specified time step. Firstly, the existing surface depth, including the rainfall depth added during the time step, is reduced by the infiltration capacity of the grid cell's occupying soil, based on the user-specified Green and Ampt parameters. Then the remaining surface depth, if any, is routed to adjacent cells according to the water surface slope. The overland flow is routed in two orthogonal directions within each grid cell. The model also enables simulation of run-on and subsequent reinfiltration, which occurs when surface runoff from upstream cells infiltrates into pervious downstream cells. Finally, the runoff from overland cells which reaches the channel cells is routed through the channel network to the watershed outlet.

CASC2D provides the user with a number of simulation options, including a visual colour display of both the static and dynamic characteristics of the watershed simulation. The static windows include colour-coded maps depicting categories of elevation, soil texture, surface roughness and land-use areas. The dynamic display has four windows that appear simultaneously when the simulation begins. Three of these windows depict the spatial distribution of rainfall intensity, infiltration depth and surface water depth. The fourth window provides a display of the outflow hydrograph as the simulation progresses.

BRIEF DESCRIPTION OF GRASS

GRASS is a fully documented, raster-based GIS that was initially developed by the US Army for natural resources and land management applications at federal installations (US Army, 1991). GRASS has been

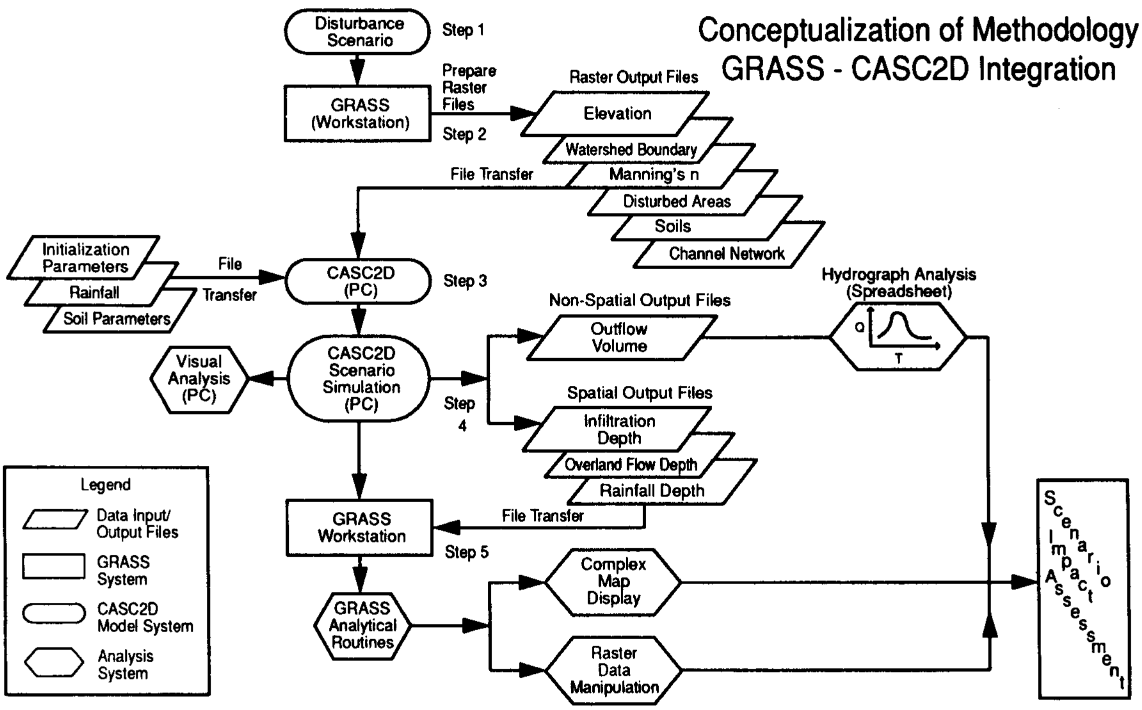

Figure 1. Five-step methodology for GRASS–CASC2D integration

coupled with a variety of hydrological models to examine environmental processes within watersheds. For example, Chen *et al.* (1994) integrated GRASS with a phosphorus transport model to study agricultural land-use and non-point source phosphorus loading in a small watershed in Oklahoma.

GRASS contains a number of advanced programs for hydrological analysis to include routines that delineate sub-watershed boundaries and channel networks from digital elevation model (DEM) data. These routines greatly simplify watershed delineation and characterization for hydrological modelling applications. As with most GIS–modelling applications, the time-consuming derivation of the digital information from primary sources is the critical first step. A GRASS data set for Taylor Arroyo was made available by the US Army, which greatly facilitated the CASC2D–GRASS integration process.

INTEGRATED CASC2D–GRASS METHODOLOGY

A five-step methodology, as shown in Figure 1, was used to assess the impacts of multiple land-use scenarios on the Taylor Arroyo watershed. The approach demonstrated, although specific to CASC2D and GRASS, more importantly provides a framework for similar analysis of land-use impacts on watersheds using other GISs and distributed hydrological models.

Step 1: scenario development

A wide range of potential scenarios can be developed and tested using the approach described. It is recommended that these scenarios are developed in concert with the land manager or other knowledgeable staff so that they represent a realistic spectrum of possible impacts. To illustrate the potential for this type of analysis, three land-use disturbance scenarios for the Taylor Arroyo watershed were developed from generalized land management concepts for the watershed. As described in the following and shown in Figure 2, each land-use scenario defines a different level of land-use impacts with regards to both the intensity and areal extent of use: (1) The increased protection scenario was defined as medium intensity usage over

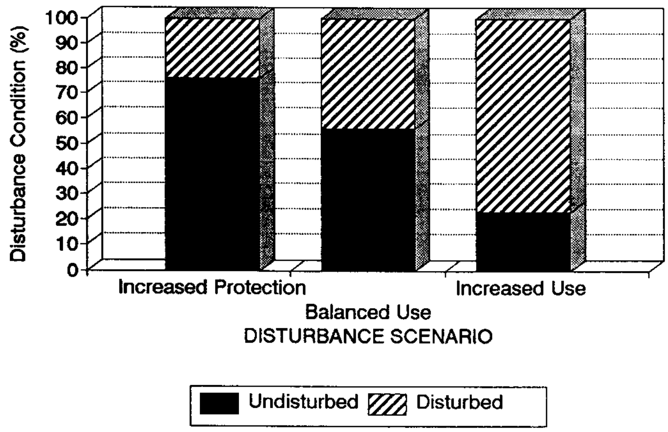

Figure 2. Percentage disturbed and undisturbed areas for generalized land-use scenarios

25% of the watershed area; (2) The balanced use scenario was defined as medium intensity usage over 50% of the watershed area; and (3) The increased use scenario was defined as high intensity usage over 75% of the watershed area.

The medium and high intensity disturbance levels were quantified as the percentage change in porosity due to compaction of the soil based on the results of *in situ* infiltrometer tests for natural conditions and after the passage of tracked vehicles (Doe, 1992). Texture-based values of the soil hydraulic properties for a 10 and 20% change in porosity were determined using the techniques described by Rawls and Brakensiek (1983). Based on the assigned soil texture, each grid cell with a disturbed soil was assigned new parameter values for the Green–Ampt infiltration equation, to include effective soil porosity, soil capillary pressure head (cm) and soil hydraulic conductivity (cm/h), to distinguish them from undisturbed grid cell values. The disturbed parameter values were distributed to the appropriate grid cells across the watershed according to the defined disturbance scenario.

Because of the variability of soils and other natural characteristics throughout the watershed, the spatial distribution of land-use impacts has a significant effect on the overall watershed response as well as on the internal watershed dynamics. The percentage of disturbed area for each scenario was allocated across the watershed in GRASS. Several contiguous areas of disturbance within the watershed were defined under the assumption that land-use tends to be concentrated in areas rather than distributed uniformly. The delineation of potentially disturbed areas in the watershed could be digitized directly from topographic maps or other sources into GRASS if that information is available to the land manager.

Step 2: spatial characterization of the watershed in GRASS

Before the prescribed rainfall events and land-use scenarios can be simulated in the CASC2D model, the physical dimensions and spatial attributes of the watershed had to be defined and input to the model as raster (grid cell) files. The raster data handling and manipulation capabilities of GRASS made this a convenient and efficient system for characterizing the watershed from digital data. The inherent spatial variability found within the watershed was characterized at grid cell resolution in GRASS. A grid cell resolution of 300 m was selected.

The basic raster map layers needed to characterize the watershed in the CASC2D model included (1) watershed boundary, (2) elevation, (3) soil texture classes, (4) Manning's n overland flow resistance classes and (5) channel network. In addition, for each scenario a soil map layer indicating the spatial coverage of disturbed areas had to be created because these soils would show different hydraulic properties. Each of these raster layers was produced, as illustrated through CASC2D graphics capability in Figure 3, using an array of standard GRASS routines for data import, conversion, manipulation and analysis.

Digital elevation model data at 30 m resolution were obtained from the USGS. The DEM data were smoothed, filtered and regridded to 300 m resolution using the suite of DEM import routines and neighbourhood smoothing filters. Once a seamless and smoothed elevation map was created, the watershed routines in GRASS were used with the DEM elevation data to delineate the subwatershed boundaries. The channel network was digitized separately based on DEM data, topographic maps and field observations. The resultant output maps were reclassified to provide a mask of the watershed for grid cell analysis. The masked area inside the watershed boundary consisted of a 46 × 60 grid cell matrix.

A digital map of Soil Conservation Service undisturbed soil classifications was reclassified into five textural soil categories based on the available soil information and field samples. The five textural soil groups identified were (1) rock, (2) clay, (3) clay loam, (4) loam and (5) sandy loam. The values of the soil hydraulic properties for each soil texture category were derived from field sampling and published tabular values from Rawls *et al.* (1983).

A digital map of vegetation classes derived from 1:40 000 scale aerial photography was reclassified into four classes of Manning's *n* overland flow resistance categories based on observed field data and published reports. Each vegetation category was assigned a value of *n* based on published tables from Woolhiser (1975).

Finally, the channel delineation produced by the GRASS watershed routines was reclassified and thinned to a one cell wide network. As reported by Fairfield and Leymarie (1991), difficulties are associated with deriving drainage networks from DEM data. The data capture processes used to derive DEM data and the deterministic eight-neighbourhood method of determining flow direction in a raster GIS can often lead to data bias that is engendered by the sampling grid orientation. This bias is particularly evident in moderate terrain with fairly uniform slopes and can result in parallel flow lines that are unnatural. The channel network produced from the 30 m DEM data had a density comparable with that of the 1:24 000 scale topographic maps, although the directional bias was apparent and several tributary junctions were misrepresented. When the channel network was delineated from the 300 m resolution data, the results were more satisfactory, although the channel network was obviously less detailed. The network delineated at the 300 m resolution consisted of 176 grid cells or approximately 13% of the total number of elements inside the watershed.

Step 3: Linkage of GRASS spatial data with the CASC2D model

The standard data export and conversion routines in GRASS were used to convert the decribed raster map layers into ASCII text files that could be then be imported directly into the model on a desktop computer.

With the exception of the channel network file, all of the GRASS-produced raster map files were read directly into the appropriate CASC2D model file without modification. Static map displays of elevation, soil textural categories, surface roughness categories and disturbance categories can be displayed in the model if desired. The modified channel network was divided into channel segments indicating the location of each element in the segment as well as the physical characteristics of the segment (width, depth and Manning's *n* roughness value).

After the raster map data files were imported, the data initialization file was prepared in the model. This file contains information on gauge locations, number of channel segments, values of Manning overland flow roughness and values of soil hydraulic properties for each soil type. The file also contains essential information on model time step, rainfall descriptors and graphics visualization routines.

Step 4: Hydrological simulation of scenarios in CASC2D and hydrograph analysis

Once the watershed characterization was complete for all raster inputs and the non-distributed parameter values were initialized, selected land-use scenarios were simulated in the model. Typically each rainfall–runoff event was simulated for a 25 h period. Depending on the simulation time step chosen, the graphics routines used, and the computer speed, a simulation would run for 60–90 min for an average simulation/measured ratio of 1:20. If visualization of the rainfall and the watershed response is desired, the full graphics capability can be used to display windows depicting the dynamic changes in rainfall intensity, infiltration depth, overland and channel flow depth and outlet hydrograph. As illustrated in Figure 4, the visualization routines are particularly valuable for observing where and when water flows from various

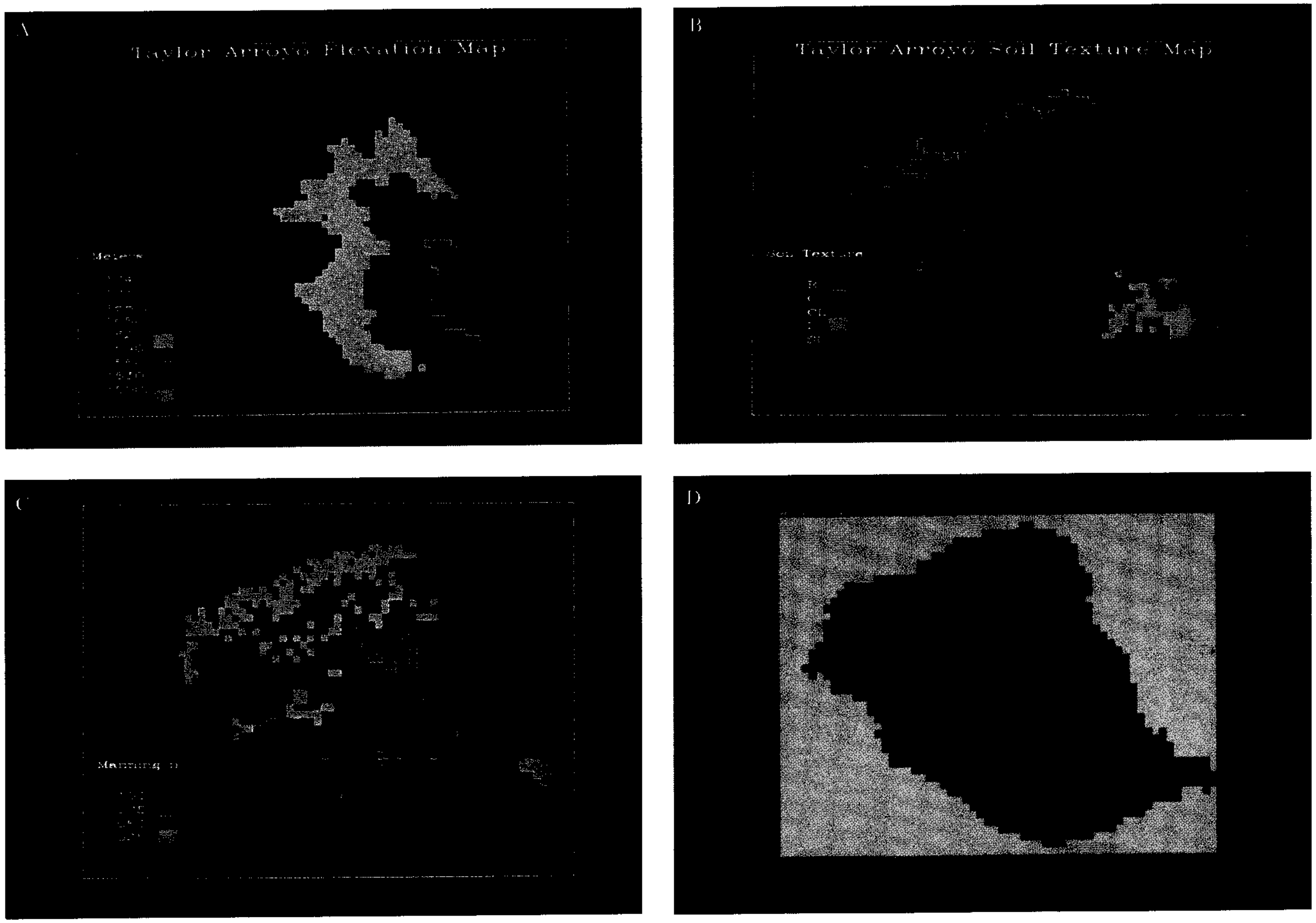

Figure 3. GRASS-generated raster maps for characterization of the Taylor Arroyo in CASC2D; (A) elevation (B) soil texture; (C) Manning's n; and (D) channel network

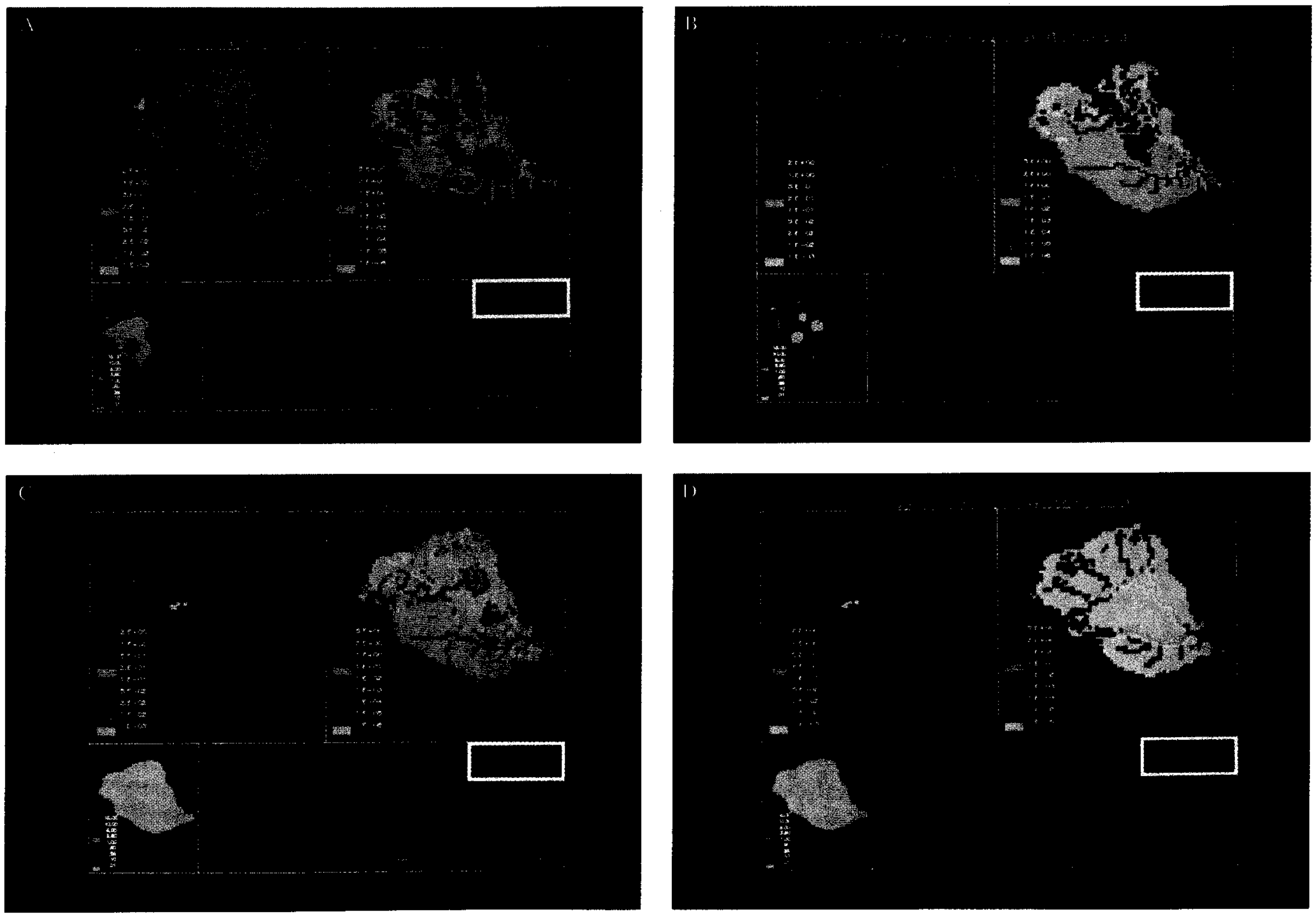

Figure 4. CASC2D simulation showing dynamic visualization graphics for a non-uniform rainfall case at; (A) 52; (B) 172; (C) 252; and (D) 904 min

portions of the watershed to the channel network and ultimately to the watershed outlet. The hydrograph for the increased use case is shown in Figure 5.

The model can be run without the visualization routines if the user is only interested in the model outputs from a scenario. In either instance the standard outputs from the model include (1) time-dependent discharge (hydrograph) in cubic feet per second (cfs) at the outlet, (2) mass balance computations for rainfall input, infiltration, surface storage and outflow and (3) final infiltration and overland flow depths (mm) at the end of simulation time for each grid cell. The model can be modified to provide the spatial outputs of infiltration and overland flow depths for any desired time step during the simulation. In this fashion a quantitative snapshot of these processes at any point during the simulation can be obtained.

The hydrograph data produced by the simulation can be easily imported into a computer spreadsheet for analysis and graphical plotting. Hydrograph envelopes, as shown in Figure 5, can be created to illustrate the watershed response under a variety of land-use scenarios. These hydrographs are useful for comparison with base case (undisturbed) scenarios. The percentage of rainfall that is infiltrated, stored or discharged from the watershed can be computed from the mass balance statistics and provides an additional quantitative assessment of how various scenarios affect the watershed.

Although the discussed data outputs provide useful quantitative information on the aggregated response of the watershed, they do not give information about the internal watershed dynamics. The model's raster outputs of infiltration depth and overland flow depth provide spatial information that can be analysed in a variety of ways. These data can be analysed by importing them into a spreadsheet and computing histograms of depth at various time intervals. These types of displays can reveal similarities or trends between scenarios that may provide useful information for management consideration. However, this type of analysis does not fully use the potential of the spatial information gained from the two-dimensional model simulation. Further analysis can be achieved by importing the simulation results back into GRASS for detailed spatial analysis and post-processing using the suite of analytical functions available.

Step 5: Linkage of CASC2D spatial outputs to GRASS for spatial analysis

The entire range of raster computational and analytical functions in GRASS can be used to manipulate and display the model outputs for further analysis. For example, the infiltration depth values can be correlated with other map layers, such as soils or vegetation, to explore significant spatial coincidences between infiltration and watershed surface characteristics. The infiltration data can be reclassified into more meaningful categories for management decision-making. Map calculations can be performed to compare the percentage differences in infiltration from various scenarios across each element of the watershed.

A raster map of the percentage difference in infiltration depth between the undisturbed and disturbed conditions for a representative scenario was derived in GRASS using the raster map calculation routines. This map is then reclassified into seven categories indicating the degree of increase or decrease in infiltration depth. This spatial data manipulation transforms the model outputs into more meaningful management information for the delineation of sensitive areas within the watershed. The model outputs can be further combined with other map layer categories using expert-derived inference rules to identify hydrologically sensitive areas. Such an approach can provide the land manager with spatially distributed information on the watershed response to various land-use scenarios that he or she contemplates.

USER CONSIDERATIONS FOR INTEGRATING HYDROLOGICAL MODELS WITH GISs

The integration of advanced hydrological models with GIS technology should not be viewed as a panacea for solving the complexities of watershed processes. However, there are several clear advantages of this integration which can be exploited, as shown by the CASC2D-GRASS approach. Maidment (1991) provides a comprehensive discussion of the advantages afforded by the modelling–GIS linkage. These advantages include the ability of a GIS to provide a digital database representing the land surface environment, without having to measure or planimeter the data from maps and other sources, and the capabilities of a GIS to act as a display environment for hydrological model outputs.

Despite the obvious advantages and capabilities of such integrated systems there remain serious concerns

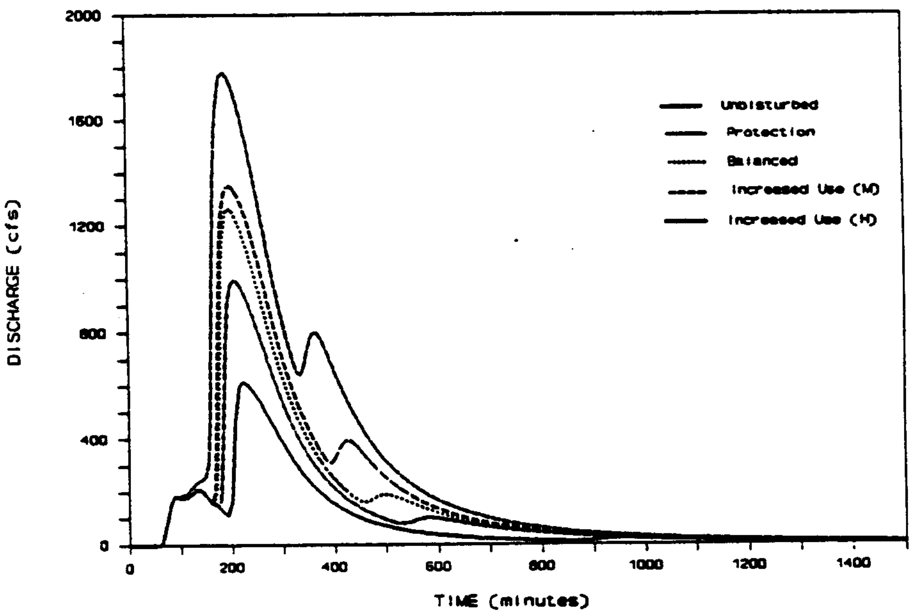

Figure 5. Envelope of scenario hydrographs for a uniform rainfall case

with regard to the quality of data, parameter estimation and grid cell scale and how these affect the representation of hydrological processes. Loague and Gander (1990) performed a comprehensive study of spatial variability of infiltration within a watershed and addressed the implications of this variability in attempting to model rainfall–runoff events, particularly when the simulation scale and parameter measurement scales are different. Field-based measurements of infiltration and hydraulic properties of the soil are suspect when extrapolated across large watersheds. The determination of grid cell scale for hydrological simulation is a major issue surrounding the use of distributed models, which is affected by a number of factors, including the original resolution of the spatial data, the governing equations and computational power of the system. In some respects, the capabilities and sophistication of hydrological models and GIS technology have exceeded our ability to provide the necessary input data given the natural variability inherent in the watershed system. Recognizing these limitations, the hydrological community should continue to foster the development and integration of spatial systems and explore the potential they provide for better understanding of land-use impacts on natural hydrological processes.

CONCLUSIONS

A series of land-use scenarios and rainfall events were simulated on a 50-square mile, semi-arid watershed, the Taylor Arroyo, using a five-step methodology that integrates the CASC2D hydrological model and the GRASS GIS. This integration was successful in depicting the temporally and spatially varied response of the watershed under different scenarios. Although CASC2D and GRASS were well suited for this specific application, the methodology illustrates the potential for other distributed modelling–GIS systems to analyse a variety of hydrological processes and associated land-use impacts. The technology and analytical methodology provided by this integration can provide otherwise unrecognized information and insights into the hydrological regime of a watershed. This added dimension can assist land managers in determining sensitive areas and future land management practices within a watershed.

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