MAPHYD — A Digital Map-Based Hydrologic Modeling System

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ABSTRACT: A digital map-based hydrologic modeling system, called MAPHYD, has been developed and applied to urban watersheds. MAPHYD incorporates automatic generation of model input data using geographic information system functions and a suite of hydrologic modeling algorithms into a user-friendly PC workstation. Interactive computer graphics techniques were used to quickly develop a watershed digital database on topography, soils, landuse, and rainfall distribution. The spatial distribution of the data are mapped as color codes which can be interpreted by the linked hydrologic response algorithms. Digital terrain modeling was accomplished to obtain slope and the direction of slope for a user-selectable grid cell resolution. Rainfall patterns were defined using radar rainfall images. Computations of runoff were based on unit hydrograph, time-area, or cascade-of-reservoirs algorithms, and various infiltration mechanisms were provided. Alternate output displays include the runoff hydrograph and the spatial distribution of runoff using an interval color scale.

INTRODUCTION

HYDROLOGIC MODELS are inherently map-based and provide a productive area for application of geographic information systems techniques. A hydrologic rainfall/runoff model, called MAPHYD, has been developed which integrates digital maps, interactive computer graphics, and a library of hydrologic response algorithms into a workstation system capable of (semi)automatic hydrologic data management and model development.

Hydrologic models incorporated into MAPHYD and integrated with the digital map database include unit hydrograph, time-area, partial area-variable source, and cascade of reservoirs. Infiltration algorithms included are the Phi-Index, Horton's, and Dunne's. Between-event soil moisture accounting is based on Thorntwaite's method. For the methods used, watershed topography, soils, land use, groundwater table position, and rainfall patterns are the primary data sets of interest. From these can be derived model parameters of drainage pattern, slope, infiltration and other abstractions, soil moisture, and rainfall inputs. A primary rainfall input is radar-rainfall imagery.

Previous hydrologic modeling efforts have been hampered by limitations on data and processing for input to hydrologic models. Recently developed methods for digital data capture, image processing and interactive computer graphics, and geographic information system software provide the tools to incorporate greater spatial and temporal detail into deterministic rainfall-runoff models.

Hydrologic model parameters are predominantly derived from mapped attributes of the land. Watershed topography, soils, land use, and rainfall patterns are the primary data sets of interest. From these can be derived model parameters of drainage pattern, slope, infiltration and other abstractions, soil moisture, and rainfall inputs.

MAPHYD is demonstrated using the Lena Gulch watershed, an urbanizing drainage system located on the west side of Denver, Colorado. Lena Gulch has an area of 25 sq km. The watershed is instrumented with radio-signal-reporting rain and stream gauges as part of a flood warning program developed by the Denver Urban Drainage and Flood Control District.

Comparisons are made to accepted rainfall-runoff models as a means of model validation. Simulations involving storm placement, size, and intensity were conducted to study the effects of temporal and spatial characteristics of rainfall. Simulations were also performed to study the effects, if any, that a variable source model has on a storm hydrograph.

BACKGROUND

GEOGRAPHIC INFORMATION SYSTEMS

Geographic informations systems (GIS) software and hardware tools were integrated into a flexible, adaptive interactive computer-graphics-based data manager supportive to automatic modeling of watersheds. Because there are many subjective aspects of watershed modeling and flood forecasting, the interactive and user-friendly character of the MAPHYD workstation permits the operator to incorporate his/her judgments into the database development, and to control the rainfall-runoff analysis process. MAPHYD also has integrated geographic information systems' functions for watershed data management.

There are a variety of methods for establishing digital data bases. The interactive computer graphics system provides an easy means for inputting, editing, and displaying data and for integrating computational algorithms directly with the digital database. Digital maps of watershed characteristics were obtained using direct entry imaging, manual digitizing, and remote sensing methods. Source maps typically include maps of topography, soils, and land use/zoning. The maps were obtained in digital formats for some attributes (e.g., digital terrain model, radar-rainfall imagery) or as paper stock obtained from a local planning agency. Radar-rainfall imagery was obtained by networking to a central mainframe computer.

Once in digital format, it was possible to archive the digital data sets and retrieve selected data to support rainfall-runoff computations. The maps were preprocessed for scale resolution, drainage system definition, and parameter estimations. Soil moisture accounts are updated periodically between rainfall events. Interactive map overlay methods are used to determine composite runoff characteristics and to input rainfall distribution.

MAPHYD was implemented on a desktop personal microcomputer, having 1.6 mb random access memory, math coprocessor chip, and MS-DOS 3.1 operating system. Graphic displays are executed by a Vectrix VX/PC graphics card set with a high resolution color monitor providing 672 by 480-pixel (picture element) resolution and nine bitplanes of graphic memory. Enhanced configuration allows 512 displayable colors selectable from 16.8 million. A digitizing tablet with four-button puck enables a user-display interface that functions as a command pick device and allows the user to trace watershed characteristics onto a (registered) digital base map. Keyboard input, displayed on a separate monochrome monitor, and output data selections

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are minimized using the menu command approach. Total cost of the workstation was less than $10,000.

The workstation functionality is representative of a new class of water resource decision support systems (Johnson, 1986). Graphics software developed for computer-aided planning (French and Taylor, 1986) was used to provide utility routines for menu definition and selection, image storage and retrieval, map mosaicking, and color overlays.

Tablet digitizing of points and lines using a vector-based format was used to define the stream network and basin boundaries. Data in vector formats are appropriate for drainage system network and boundary definition and are becoming more standardized. Many vector data sets can be obtained from government sources (e.g., Census DIME files, USGS Digital Line Graphs) or private vendors.

In MAPHYD, many data can be represented as colors, and input/editing of watershed data can be accomplished using "painting" functions and paper map data digitizing from the tablet. The tablet coordinate space can be referenced to the image coordinate space; thereafter, data digitized from the tablet is translated and displayed in image space. This scale resolving function permitted data extraction from maps with differing scales. Data for large and small areas were input and edited for model parameter modifications as part of calibration.

Image digitizing was another primary means of providing a representation of an image (e.g., map, photograph, or remote scene) in computer compatible form. The image, or raster, format was in contrast to the vector format noted above. Image digitizing methods required special-purpose computer hardware which converts light intensity observed at a particular location within a scene to a digital representation with the color attributes red, green, and blue. The digital imagery can be interpreted as data, and as a location framework for display of other manually digitized, imported, or computer-generated data.

Other nongraphic, tabular data files were incorporated into the MAPHYD system using the coordinate location as a primitive key or index. Such data may be associated with points, lines, and polygons/areas. Examples include the station records recorded at a streamflow gaging station, and the age and maintenance history associated with a particular pipe or valve in a water distribution system. The relational database management system is an appropriate choice for handling alphanumeric data keyed to a graphic entity. Calls to a DBMS can be standardized on many computer systems using the SQL (Structured Query Language) conventions.

Defining Hydrologic System Characteristics

Base maps of the Lena Gulch watershed were input using video digitized topographic maps and were mosaicked to form the watershed base map (Figure 1). There are a spectrum of digital maps which portray the watershed and storm data to be processed: composite soil/landuse, elevation, groundwater, upslope distance, and precipitation. Colors are overlaid as transparencies on the gray scale base map, a technique which provides immediate visual feedback on location.

Each computational element has these data attributes, and the user can vary the element size in support of simulation experiments. MAPHYD has the flexibility to vary the unit computational size from a picture element representing a land area of 30 metres square (900 sq m) to as large as the user desires. This flexibility provides a way to study the full effect that computation element resolution has on the rainfall-runoff model results.

Figures 1 through 8 and Plates 1 through 4 present digital datasets used for the Lena Gulch watershed simulation modeling. Figure 1 is the digital base map obtained using a video image capture or direct entry camera device. Separate maps can be mosaicked to form a watershed base map upon which (color-coded) land attribute data of various types can be registered and applied.

FIG. 1. A digital base map of the Lena Gulch watershed area obtained by video image capture techniques. The base map was formed by mosaicking separate images to form the complete 25 sq km watershed map.

FIG. 2. Digital terrain model of the Lena Gulch watershed, defining elevations for each picture element. It was formed by tracing contour bands visible on the displayed digital base map.

Topography of the Lena Gulch watershed was defined by color coding of the elevation contour bands visible on the digital base map (Figure 2). The highly refined digital terrain model shown was developed in order to obtain as much detail on elevations as possible. This was to support later experiments in which the spatial resolution of the terrain data was degraded and the impact on the predicted runoff hydrograph observed.

The elevation map was processed to obtain slope parameters (Plate 1) and runoff directions and distances (Plate 2). A slope classification map was generated from the digital terrain model (Ritter, 1987). Slope has a strong influence on the hydraulics of overland and channel flow, and is an essential parameter for rainfall-runoff modeling. Aspect map displays the facing compass direction and was derived from the digital terrain model. Aspect

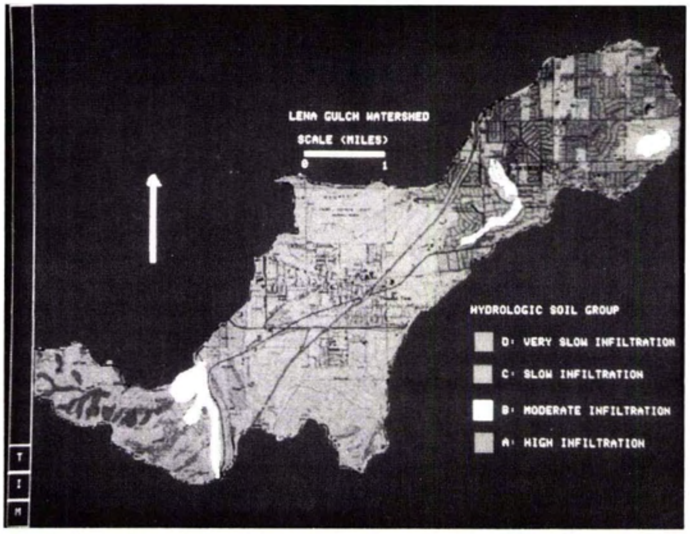

FIG. 3. Soils data obtained from SCS soils maps and categorized into four hydrologic soils groupings per their infiltration capacity and rate.

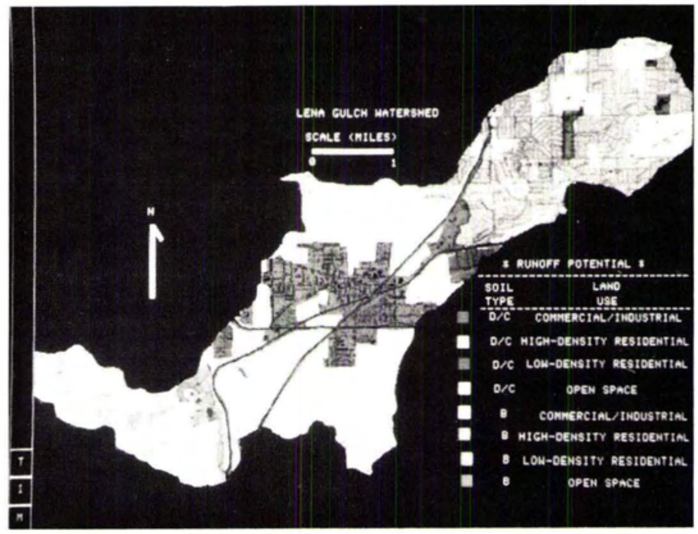

FIG. 5. A composite map defining runoff potential, generated from an overlay of the land-use attribute map onto the soils map.

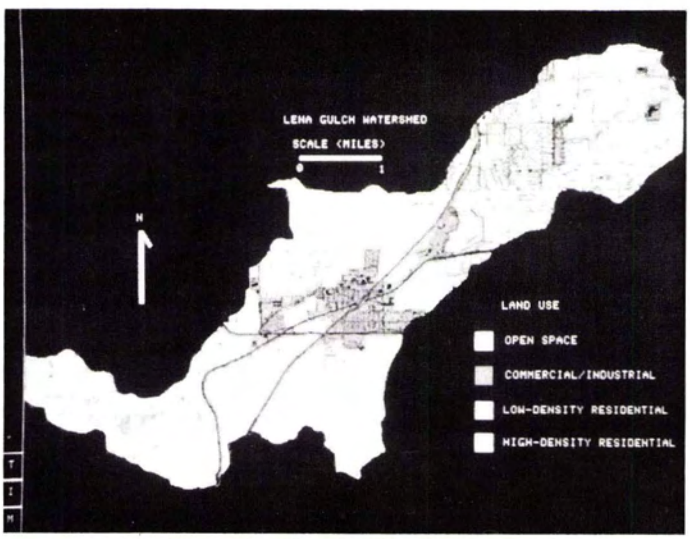

FIG. 4. Land-use data obtained from local land-use and zoning maps and digitized onto the watershed base map.

FIG. 6. Depth to groundwater map. Used to determine partial area where direct runoff occurs, much like impervious areas of streets and rooftops.

determines the direction of flow, one cell to another, and aspect data can be used to define the drainage pattern.

A basic digital dataset to support infiltration and other abstractions accounting was the soil map (Figure 3). Here the Soil Conservation Service (SCS) hydrologic soils group data were hand-digitized on the watershed base map. There are two different soil parameters – porosity and saturated hydraulic conductivity – for each soil group.

Landuse data (Figure 4) play a very important role in computing the excess precipitation from a watershed. In areas of high density land development, the calculated percent of imperviousness will reflect areas of little or no infiltration capacity. The MAPHYD procedure involves digital mapping of commercial, high density residential, low density residential, and open space landuse types. Four levels of land imperviousness were used to describe the watershed's landuse. The program's default settings are 90, 70, 50, and 2 percent impervious for commercial, high density residential, low density residential, and open space, respectively (Urban Drainage and Flood Control District, 1985).

The soils and landuse maps were logically combined to form a composite runoff potential map (Figure 5). The runoff potential map derived reflects a matrix of combinations of soil and landuse categories having distinct pervious-impervious area characteristics.

A depth-to-groundwater map (Figure 6) represents the depth of groundwater from the land surface. MAPHYD automatically estimates the initial groundwater depth using a characteristic elliptical curve derived out of the Dupuit-Forchheimer assumptions of unconfined flow through porous media. The governing equation represents a solution to the Dupuit-Forchheimer equation with steady state groundwater recharge developed by Freeze (1980).

Runoff potential (soils and landuse) and depth-to-groundwater were combined to support rainfall infiltration and abstractions

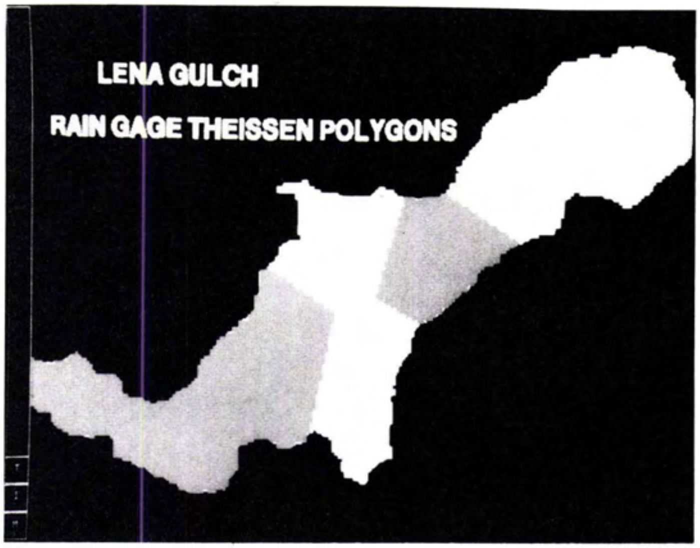

FIG. 7. The watershed area associated with each rain gauge, determined by implementing the Theissen polygon procedure.

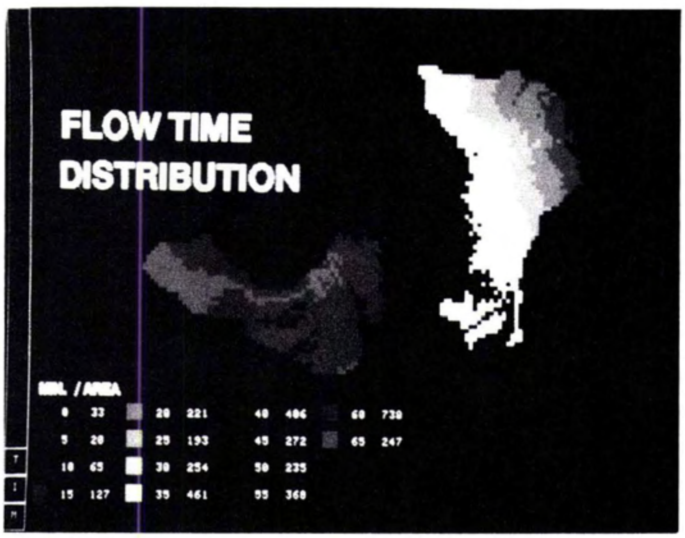

FIG. 8. Isochronal contours of equal flow time, generated using equations of overland and channel flow, inputs for which were obtained from the digital map data sets.

computations. Excess precipitation was determined to be sensitive to soil and landuse parameters. The program calculated the values for each pixel within the computational unit as well as a weighted average for the each computational unit.

If only point rainfall data are available at sites of rain gauges, it is standard hydrologic analysis procedure to determine the area assignments associated with each gauge. The so-called "Thiessen polygon" procedure was readily implemented as a GIS function (Figure 7) as were other geometry-based algorithms.

Rainfall distribution was also defined using radar-rainfall imagery (Plate 3). The overlay operation provides great detail on the spatial distribution of rainfall. Storm duration and time distribution of rainfall were also defined by moving the image using the interactive graphic data manipulation techniques.

Isochronal contours of flow time from each basin location to the outlet were generated using equations of overland and channel flow (Figure 8). Runoff magnitude (Plate 4) and other model-generated data were displayed on the base map and provide a quick visual key of the location of high flows.

MAPHYD Hydrologic Models

MAPHYD hydrologic simulation models performed calculations of incident rainfall, contributing areas, infiltration rates, soil moisture content, evapotranspiration, water table positions, and overland flow and channel routing using the digital map database as inputs. The models use parametric equations for areas of infiltration, groundwater flow, initial abstraction losses, excess precipitation, and flow routings.

All models were implemented using the interactive command programming approach. That is, geographic data processing for model parameter estimations, as well as model procedure selection and activation, are controlled using menu commands. If new geographic data are to be entered, the command program accesses the geographic database program which in turn provides the means of entering, editing, displaying, and storing the digital spatial data. The menu commands also provide access to the available model functions for analyzing and using the data. Built-in "help" commands display user instructions and serve as an interactive aid for teaching watershed modeling methods.

A spectrum of hydrologic models have been integrated into MAPHYD as summarized below. Comparisons were made to accepted rainfall-runoff models (e.g., unit hydrograph) as a means of model validation. Simulations involving storm placement, size, and intensity were conducted to study the effects of temporal and spatial characteristics of rainfall. Simulations were also performed to study the effects that alternate infiltration algorithms had on the storm hydrograph.

- *Unit Hydrograph Method*: The Colorado Unit Hydrograph Procedure (CUHP) was developed by Denver's Urban Drainage and Flood Control District (1985). Unit hydrograph model parameters derived from the geographic data sets include the basin slope, hydrologic soils group, percent impervious land, and rainfall. The UH method is a lumped parameter approach requiring averaging of watershed characteristics. MAPHYD automatically performed these data reduction and compositing operations.
- *Time-Area Method*: The time-area or isochronal method, introduced by Clark (1945) and summarized in Chow (1965), was based on preprocessing to determine the flow time from each location in the watershed to the outlet. The image so-formed was then processed in concert with the rainfall distribution images, runoff potential, and infiltration to obtain the runoff hydrograph at the basin outlet (Johnson and Dallmann, 1987). Preprocessing of the runoff timing permits very rapid computation of the basin outlet hydrograph, a factor allowing runoff computations for large areas on a microcomputer.
- *Partial Area — Variable Source Model*: Partial area refers to runoff generated from impervious and saturated lands. Particularly, the position of the groundwater table is of interest. Where it intersects the surface, rapid and total runoff will occur. A variable source model considers runoff generated from surface and subsurface flow. Eagleson (1972), Engman and Rogowski (1974), and Freeze (1980) validated the partial area concept but their models were difficult and time consuming to apply.

  In contrast to these earlier models, MAPHYD considered the entire watershed catchment and how the multiple hillslopes interact with each other from the standpoint of groundwater flow and excess precipitation during a storm event (Toms, 1987). There are several user-selectable methods for infiltration accounting built into MAPHYD, including Horton (1946), Dunne *et al.* (1975), Just Evapoartion, All Methods, Horton's With No Imperviousness, and Dunne With No Imperviousness. Evapotranspiration loss was included in MAPHYD to consider the amount of water removed between storms. The Thornthwaite equation (Criddle, 1958) was selected to reflect this loss.
- *Cascade of Reservoirs*: Complete integration of the digital terrain model and preprocessing products of slope and aspect with rainfall, infiltration, and overland and channel flow hydraulics was accomplished in MAPHYD's cascade of reservoirs model (Huffman, 1988). Here, each cell was treated as a reservoir with the basin treated as a collection of reservoirs, each cascading downslope one to another (Chow, 1964). Although computationally intensive,

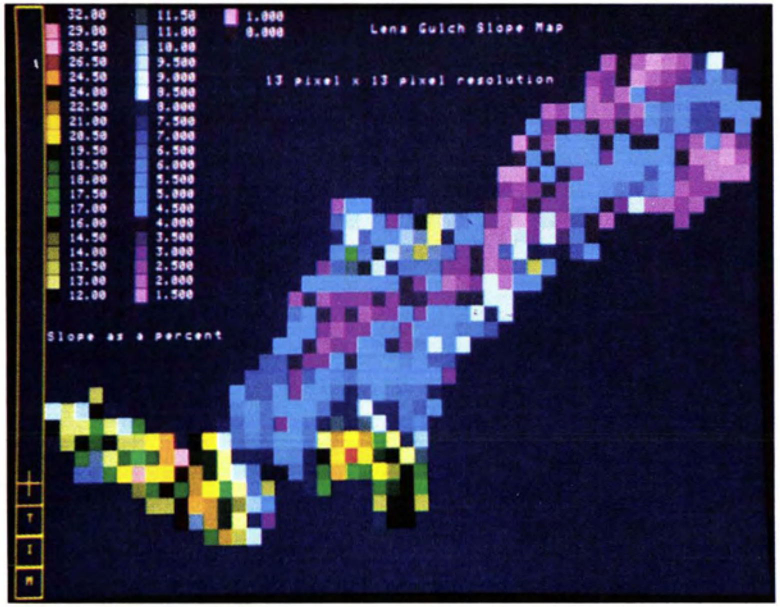

PLATE 1. Slope classification map generated from a digital terrain model. Slope has a strong influence on the hydraulics of overland and channel flow, and is an essential parameter for rainfall-runoff modeling.

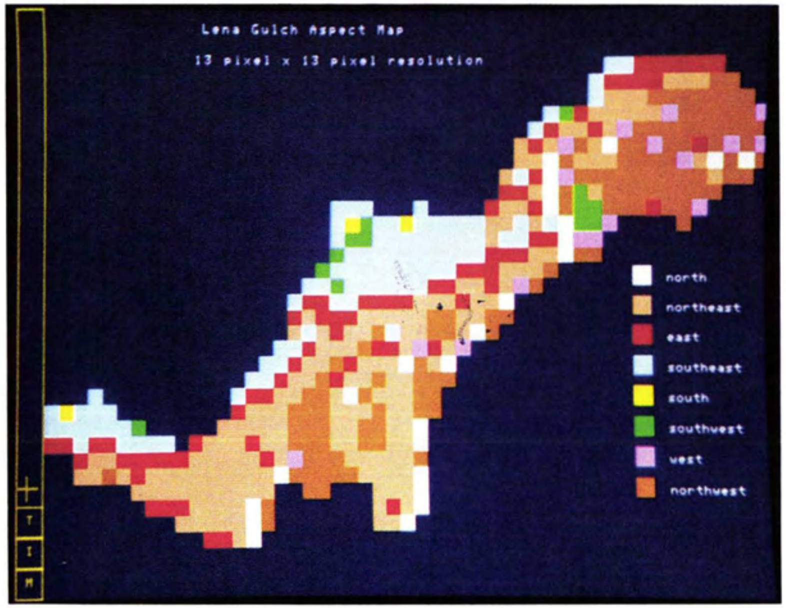

PLATE 2. Aspect map displaying the facing compass direction, derived from the digital terrain model. Aspect determines the direction of flow, one cell to another, and aspect data can be used to define the drainage pattern.

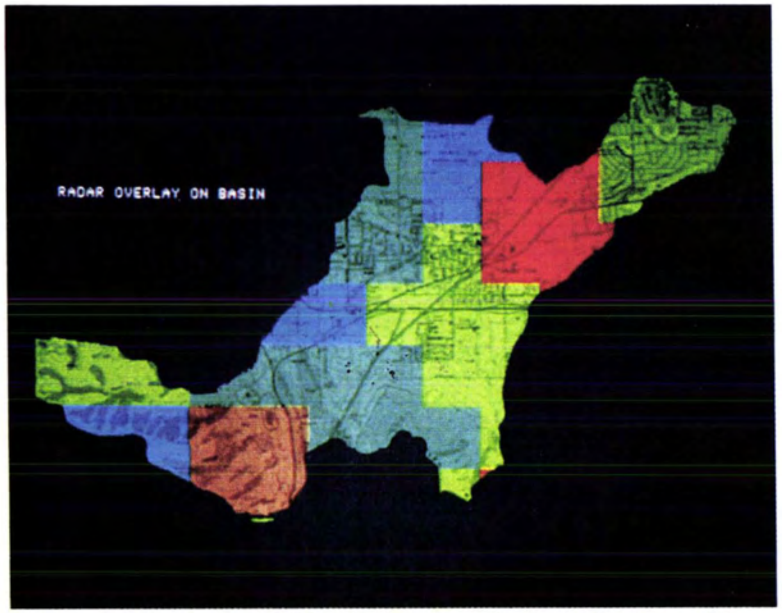

PLATE 3. Overlay of radar-rainfall image onto the watershed using geographic information systems processing techniques. Provides an efficient means for defining the spatial distribution of rainfall and its movement.

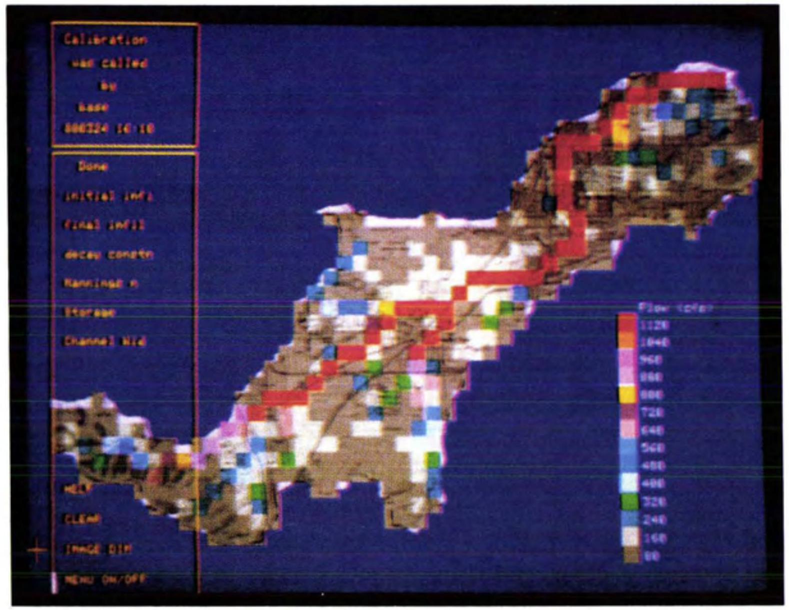

PLATE 4. Spatial distribution of runoff resultant from rainfall event displayed (color coded) at each computation time step. Locations of high flows area readily determined using this display format.

this distributed parameter model is physically based and permits simulation of the runoff hydrograph at any location in the basin.

RESULTS

The MAPHYD hydrologic modeling system was applied to the 25 sq km Lena Gulch watershed in order to take advantage of the relatively detailed engineering and topographic data sets which were available from the Denver Urban Drainage and Flood Control District (1986). Also, the watershed was instrumented with an ALERT flash flood warning system consisting of six rain gauges and three stream gauges which reported by radio signal during rainfall events to a microcomputer base station. The base station archived the data.

Unit hydrographs produced by the Colorado Unit Hydrograph Procedure (CUHP) and TR-20 (SCS, 1965) models were computed using the standard methods for design storms. The similar shape of the unit hydrograph obtained by the time-area algorithm demonstrated its relative accuracy. Several runoff events occurred during the modeling project, and the rainfall and runoff data were obtained. We were able to match runoff volumes and flow peak for one of the events without difficulty. However, none of the events were of significant magnitude to cause flows in excess of bankfull stage, thus limiting their utility for model calibrations.

The spatial distribution of rainfall across a watershed was shown to have a pronounced influence on runoff magnitude and timing. Simulation experiments were conducted using radar-rainfall imagery from another location in the region and the point gauge locations. Variability of intensities for the radar-rainfall imagery was considerable (see Plate 3) and typical for the types of thunderstorms which occur along the Colorado Front Range. The six radar-rainfall images used generally exhibited three to five intensity levels, in which two of the intensity levels covered over half of the drainage area.

A capability for moving the rainfall event was developed, which permitted examination of storm movement on flood runoff. Moving the event in a downstream direction versus an upstream direction resulted in an outlet flood peak 33 percent higher and the peak occurred at hour 1.0 instead of hour 2.5.

The areal resolution of the watershed computational element size was determined using the radar-rainfall image as input. It was determined that a maximum cell size of 1 sq km was appropriate in order to maintain computational distinction and maximum speed. Cell sizes larger than 1 sq km tended to result in large runoff hydrograph variations when the radar-rainfall image was placed at different locations.

Comparisons were made between runoff hydrographs obtained by uniform basin averaging techniques (arithmetic mean, Theissen polygons) using the six rain gauges in the Lena Gulch watershed. It was concluded that both point gauge averaging techniques failed to accurately describe the actual spatial resolution of rainfall. Assuming the radar-rainfall image to have complete accuracy, differences of greater than 30 percent occurred in the peak discharge, and time-to-peak calculations were found to be inconsistent.

The influence of impervious area runoff was demonstrated by a with- and without computation. Computation of impervious areas using MAPHYD compared closely with the control data set at 42 percent. A flood peak of 7090 cfs (cubic feet per second) was obtained when impervious area was considered, compared to a flood peak of 1780 cfs when the impervious area was ignored. In each case the Horton mechanism was used for infiltration on pervious areas.

CONCLUSIONS

Development and use of MAPHYD has demonstrated the linked capabilities for digital data management, simulation, and graphic communication of flood runoff conditions. MAPHYD provided useful and powerful tools for watershed modeling. Higher productivity is believed realized for watershed database development, modeling research, hydrologic design, and real-time flood monitoring and forecasts.

The MAPHYD models have been checked against accepted rainfall/runoff models used for engineering design. Storm hydrographs obtained from the CUHP model for Lena Gulch watershed compared well with the results generated by the MAPHYD models in terms of the shape of the hydrograph and peak discharge. Calibration and verification of the model will require further testing using monitored storm data for the coming thunderstorm seasons.

MAPHYD has the capability to quickly update hydrologic parameters either by interactive user control or through computation. Soil and landuse parameters can be initialized and updated multiple times in response to development and development proposals. Real-time data can be accessed and displayed to provide decision support functions useful for flood forecasting.

MAPHYD was more flexible than the unit hydrograph procedure and accounts for more variables. In particular, spatial variations in impervious lands and spatial and temporal variations in rainfall were shown to have a significant effect on the magnitude and timing of flood runoff. Basin averaging and lumped parameter modeling approaches can introduce substantial error in the runoff hydrographs. Also, it has been demonstrated that distributed parameter modeling can be accomplished rapidly on a microcomputer, a factor contributing to use of MAPHYD for real-time flood forecasting operations.

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