Development of a Geographic Information System for Urban Watershed Analysis

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Abstract
A geographic information system (GIS) interfaced with a distributed hydrologic model for urban watershed analysis. Basic data layers are digitized into a spatial database, and the system topological data structures are used to generate feature attributes and data products necessary for modeling. Additional programming allows the system to use the coordinate values of features in the watershed to directly calculate flow-plane geometry and routing distances of overland flow paths, gutters, and storm sewer segments. Access to coordinate values in the coverages also allows the system to automatically determine the connecting drainage network, or the order and direction of flow throughout the urban drainage area. This is a significant improvement over other systems in which the order and direction of the network must be determined and digitized by the user. The combined GIS/Modeling system is capable of analyses of urban drainage problems at a variety of scales (inlet, block, basin) and at a level of spatial detail not heretofore accomplished.

Introduction
The management of spatial information has become easier with the arrival of geographic information systems (GIS). It should now be possible to model physical processes more accurately in a complex environment using a GIS. One area in which GIS may be particularly helpful is in the hydrologic analysis of urban watersheds. For efficient and effective design, planning, and management purposes, the engineer or manager needs access to as much spatial information about the watershed as possible.

This paper describes an approach where the spatial analysis capabilities of a GIS can be used for the hydrologic analysis of an urban watershed. The attributes of watershed features stored in a GIS database were used directly in a hydrologic model to determine the runoff hydrograph. As a result, the effect of any change in watershed characteristics on the magnitude or spatial distribution of runoff from the watershed could be evaluated. The coordinate values that define the location of features in the database were used to incorporate the spatial heterogeneity of drainage basin characteristics into the hydrologic analysis.

The GIS software used for this study was ARC/INFO. In addition to being widely used, the ARC/INFO system is primarily a vector-based system. The system was used to develop a spatial database of the study area by digitizing the topography, soils, pervious and impervious areas, storm drain system, stream channel, and street network into separate layers and including their respective attribute information into the database attribute tables.

GIS and Hydrologic Modeling
Simulation of hydrologic response in urban environments can be accomplished using either conceptual or physically based methods. Conceptual models simulate the response of a basin or a portion of a basin at the outflow point. In this procedure, the conceptual model is used as a "black box" to determine the basin response when a rainfall excess pattern is applied. For this reason, the spatial variability in basin characteristics is usually lumped into the parameters of the conceptual model. The unit hydrograph (Sherman, 1932) is one outstanding example of a conceptual model.

On the other hand, physically based, or distributed, models attempt to simulate the actual physical processes involved in determining the runoff response to a given rainstorm. These processes are governed by the conservation principles of mass, momentum, and energy. Thus, the differential equations describing these processes are solved in complete or simplified form. Therefore, in this method the spatial variability in the physical watershed characteristics can be included explicitly in the modeling. Thus, greater detail in these characteristics can result in a more accurate simulation.

For instance, Figure 1 is a drawing of a typical street block to be found in an urban watershed. A physically based distributed model of this block would consist of overland flow planes (lots, streets, roof tops), routing reaches (overland, gutter), combining points (inlets, junctions), and storm sewer segments. The modeling would begin at the most upstream point from where the response was desired and proceed downstream. The rainfall is applied uniformly to the plane. The portion of rainfall that does not infiltrate or pond (rainfall excess) is calculated and routed off the plane to the gutter and routed on to the nearest storm sewer inlet. The combined flow from all contributing planes that enters the inlet is combined with the flow routed down from upstream inlets and is then routed on down the storm sewer segment. This procedure is symbolized in the routing schematic shown in Figure 2.

In order to perform this modeling, a great deal of information must be known about the area, and thus can be incorporated into the simulation. These data include soils information (infiltration rates, hydraulic conductivities, and storage capacities), surface characteristics (pervious, impervious, slope, roughness), geometry and dimensions of flow planes, routing lengths (overland, gutter, and sewer), and the

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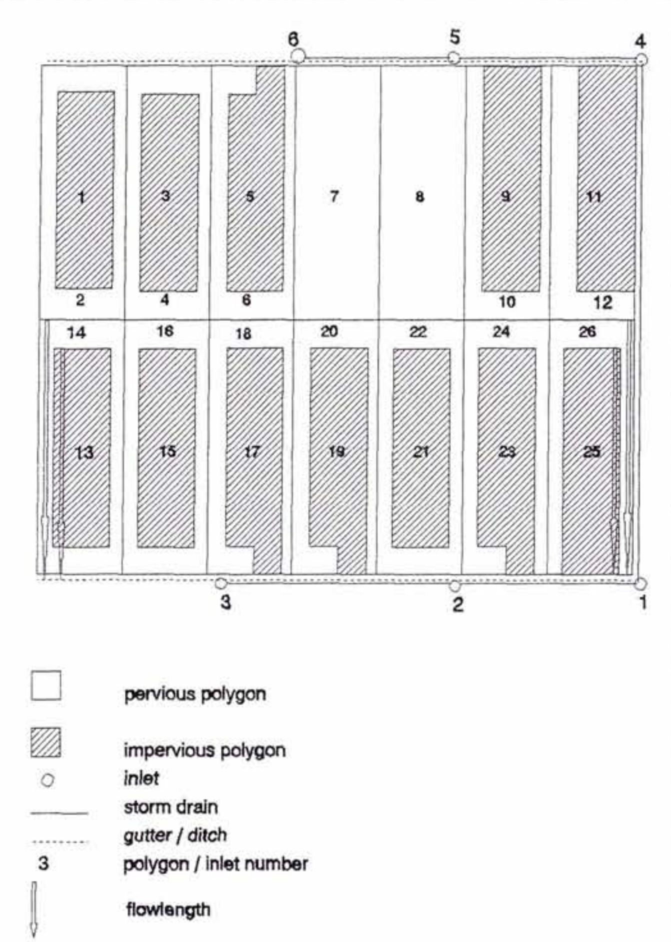

Figure 1. A typical street block for the Ward Creek watershed showing elements of the block.

geometry and characteristics of routing segments. Of course, the drainage network, or order of the planes, routing segments, and inlets above the most downstream point, is a crucial piece of information which determines the nature of the response.

A review of the literature reveals that most applications of GIS technology in hydrology have been in rural or agricultural basins. However, a few studies have directly used GIS for hydrologic analysis of urban areas (Grayman *et al.*, 1982; Johnson, 1989; Djokic and Maidment, 1991; Smith and Brilly, 1992; Kim and Ventura, 1993; Meyer *et al.*, 1993; Ventura and Kim, 1993). Most of these studies used GIS to calculate the parameters of existing lumped parameter models and to display basin characteristics. For instance, Djokic and Maidment (1991) used ARC/INFO with the rational method to determine inlet and pipe capacity of an urban storm sewer system. The overland flow paths were digitized directly and combined with a digital elevation model (DEM) based on the triangulated irregular network (TIN) to determine changes in elevation. Johnson (1989) used GIS for the generation of input data for a digital map-based modeling system that supports lumped parameter models such as unit hydrograph, time-area, and cascade of reservoirs. Cline *et al.* (1989) and Moeller (1991) used GIS to determine input parameters for the HEC-1 model, Sicar *et al.* (1991) used a GIS system to determine time-area curves, while Ragan and Kosicki (1991) used a GIS to define input parameters for the SCS hydrologic model. Kim and Ventura (1993) use a GIS system to manage and manipulate the land-use data for modeling the non-point source pollution of an urban basin using an empirical urban water quality model. However, it appears that full use of GIS capabilities in conjunction with distributed watershed modeling has not yet been accomplished.

Study Area

The upper portion of the Ward Creek watershed, north of Government Street in the city of Baton Rouge, Louisiana was selected for this study. This portion of the watershed has an area of approximately 1212.12 hectares and is predominantly mixed residential with some industrial and commercial developments (Figure 3). A fairly well developed storm drainage system drains the watershed. One feature of this system is that, in many parts of the watershed surface, drainage is accomplished via unlined ditches *in lieu* of concrete curbs or street gutters. A U.S. Geological Survey continuous stream flow station is located on the creek at the Government Street bridge, the outlet of this portion of the watershed.

Methodology

Database Development

The task of building a spatial database for the Ward Creek watershed involved the digitizing of information from various sources. Even though the data digitized were at different scales and resolutions, any effects due to those differences were considered to be minimal because the range of scales for the basic data used was small (Table 1). One exception to this, however, was that the soils data were digitized from

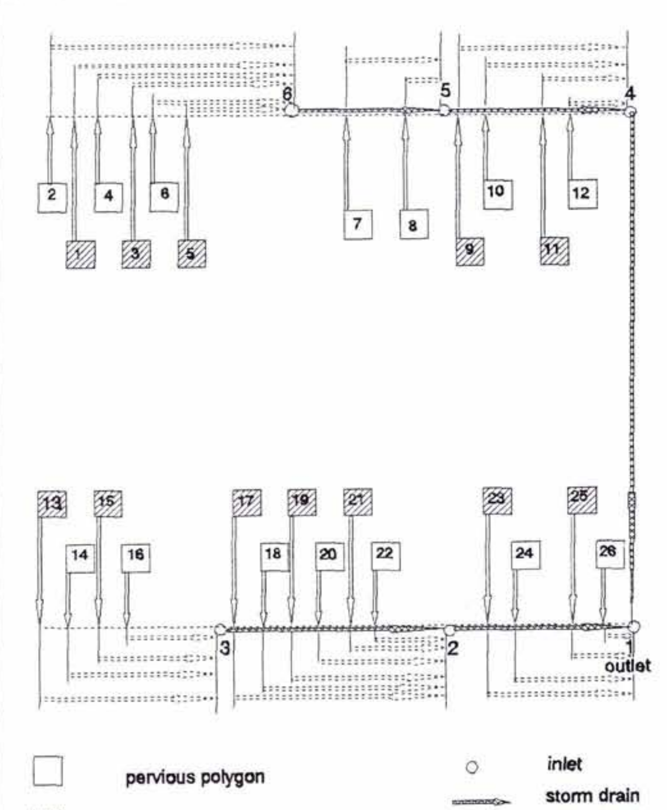

Figure 2. Drainage network and routing schematic for street block shown in Figure 1.

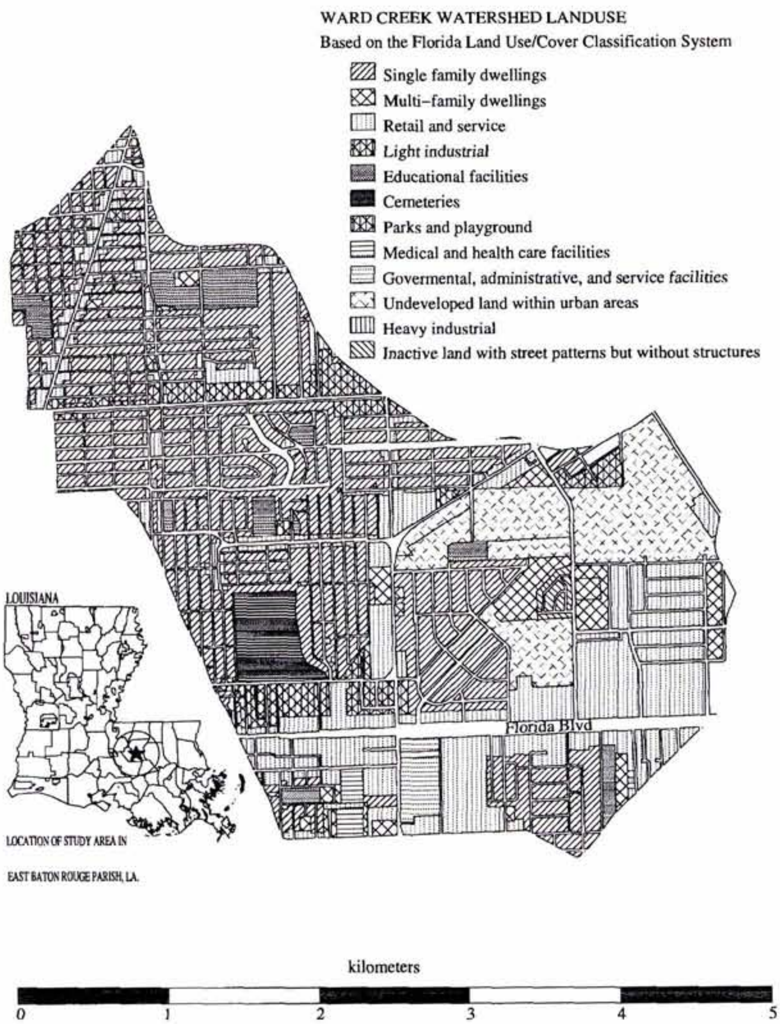

Figure 3. Land use and street network of the Upper Ward Creek watershed.

soils maps at a scale of 1:20,000. Although this scale is considerably smaller than those of the other data sources, this is not considered to be a major source of error because the variability of soil characteristics pertinent to flow modeling in the area is relatively small.

The Louisiana State Plane Coordinate System was used

TABLE 1. DATA SOURCES, SCALES, AND ATTRIBUTES FOR UPPER WARD CREEK WATERSHED.

Data	Source	Scale	Database Attributes
Topography	Topographic map from U. S. Army Corps of Engineers, New Orleans District, Louisiana	1:3600	Elevation (2ft contour)
Soil	Soil survey of East Baton Parish, Louisiana	1:20000	Soil series, area, soil type, hydrologic soil group, hydraulic conductivity, soil depth, soil thickness, available water capacity
Landuse	Zoning maps of the City-Parish Planning Commission of the City of Baton Rouge and the Parish of East Baton Rouge	1:4800	Landuse code based on the Florida Land Use/ Cover Classification System (See Figure 3)
	1992 black-and-white photographs	1:6000	
	1989 NAPP color infrared photographs	1:40000	
Pervious and Impervious Areas	1992 black-and-white photographs	1:6000	Area, Pervious (PER), Impervious (IMP), Roughness
Street Network	Zoning maps from the City-Parish Planning Commission of the City of Baton Rouge and the Parish of East Baton Rouge	1:4800	Length
Street Pavement	1992 black-and-white photographs	1:6000	Area, Pervious (PER), Impervious (IMP)
Drainage (Storm drains and Ward Creek)	Storm drains and channels project maps from the East Baton Rouge Department of Public Works	1:2400	Length, Pipe size, Shape, Roughness

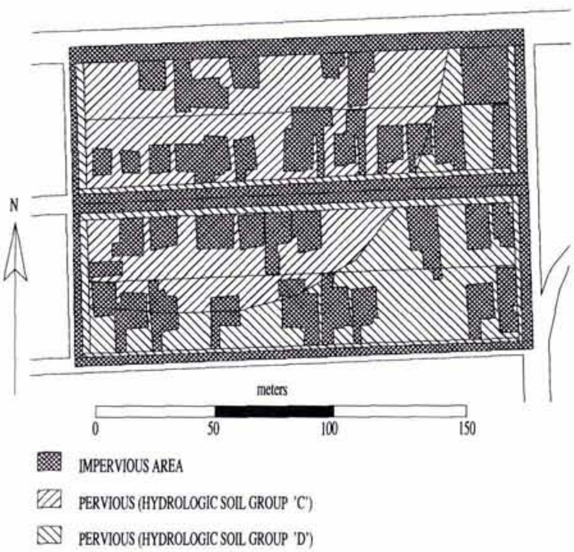

Figure 4. Pervious and impervious areas and hydrologic soil group for a two-block area of Water Creek watershed.

as a reference framework for the digitized data. Wherever possible, the same series of control points were used to reduce registration error and provide consistency among the various layers. Table 1 identified the basic data and their attributes that were included in the database. Impervious surfaces include roads, sidewalks, parking lots, and the roofs of buildings. Storm drain network records from the City of Baton Rouge Department of Public Works were incomplete and had to be supplemented by field observations.

Utilization of Spatial Database

The GIS software selected for this study, ARC/INFO, has a large number of tools that can operate on spatial data. These tools provide the means whereby the spatial database can be manipulated into a preliminary form suitable for hydrologic applications. The tools can be used for assigning feature attribute values or create new features with appropriate attributes suitable for hydrologic analysis. These tools can be applied over an entire area, or on a selected set of features within an area. For example, the Soil Conservation Service (SCS) curve number (CN) is often used in hydrologic modeling to separate the infiltrated water from the direct surface runoff. The curve number is a function of the hydrologic soil characteristics and the imperviousness of the surface. The overlay tools within a GIS will enable the combination of the soil and surface layers, together with their respective attributes, to create a new layer that is based on curve numbers, or to assign curve numbers to existing features. Through the utilization of these tools, a realistic preliminary database can be created for hydrologic modeling.

The attributes for the various layers were connected by relational tables. As a result, item values needed for analysis can be extracted or assigned based on some specific criteria. For instance, because runoff from the surface is dependent on the surface and soil characteristics, the soil layer was overlayed on the surface layer so that the soil composition could be determined. The soil feature attributes were connected to the surface features attributes through a series of relational tables. Figure 4 is a portion of the resulting layer, from the topological overlay operation with the imperviousness layer, and the soil layer. The relational tables are subsequently used to assign curve number (CN) to various surfaces. For example, pervious surfaces with soils that are categorized as in hydrologic soil group D were assigned a curve number of 80.

The information in the database can also be queried and used for various type of analyses. Values that represent attributes of features are accessed and used in numerical computations. This is facilitated by the ARC/INFO GIS through the programming concept known as cursor processing and the Arc Macro Language (AML). For example, values that represent the curve number of the surface and the soil storage capacity were accessed automatically by an AML program and used in the computation of the excess rainfall for each surface feature.

A similar approach was taken to access and use slope-related information. The contour layer was used to build a triangulated irregular network (TIN) using a horizontal sampling interval of 100 feet along each contour line. The TIN was subsequently transformed into a two-dimensional layer in order to be used with the other layers. The resulting layer with corresponding attributes provided information on slope and aspect for each triangular facet. The surface layer is overlayed with the TIN layer to access the slope for each surface feature. The overlay operation resulted in the calculation of multiple slopes for each polygon in coverage (Table 2). Depending on the requirements of the study, information could be obtained for each surface unit based on a unique soil type, slope and surface characteristics, or the surface slope profiles. In this study, the average slopes were used for every surface area with a unique soil and surface characteristics. Surface polygons with zero slope were assigned small non-zero values (0.001) during numerical computations.

A similar approach was followed to acquire slope information for the storm drains. The design of the drains depends on gravity flow for their operation. The storm drain layer was overlayed by the TIN layer based on the assumption that the slopes of the storm drains were similar to the surface. The feature attribute table that resulted from the overlay operation was subsequently used to create a table of average slope values for each storm drain segment. The relational table approach was used to access the values for use in computations. Additional data pertaining to the storm drain segments such as length, diameter, roughness, and shape were also included in the database. This approach was also used to acquire slope information for the street pavement layer.

Construction of Modeling Schematic

Several programs were written in the Arc Macro Language to extract and use information from the spatial database. These programs access the values in the feature attribute tables, determine the order of the drainage network, and calculate the plane geometry and routing lengths. In some of these opera-

TABLE 2. SURFACE SLOPE FROM TRIANGULATED IRREGULAR NETWORK (TIN).

Record	Polygon #	Slope (%)
2077	752	0.414
2078	753	0.414
2080	752	0.374
2081	755	0.374
2086	710	0.374
2087	753	0.374
2091	746	0.312
2095	710	0.312
2096	710	0.374
2097	746	0.312
2098	710	0.312
2099	760	0.312

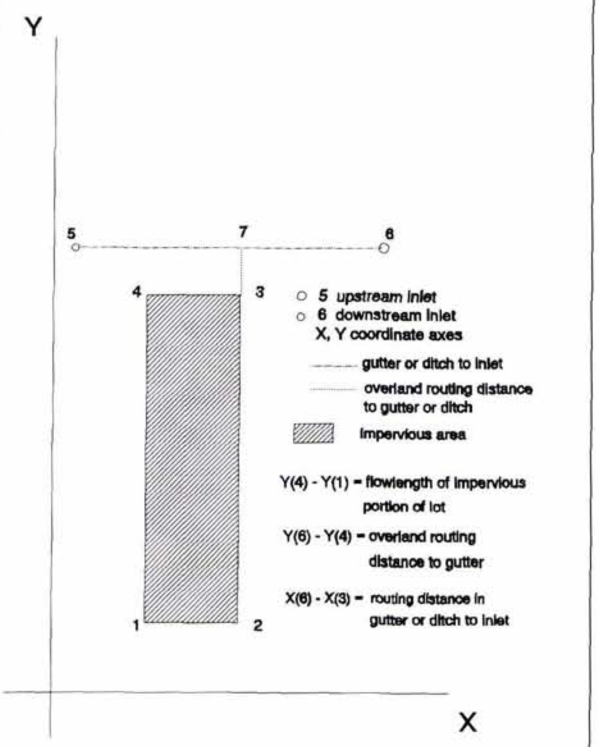

Figure 5. Schematic of an impervious area not directly adjacent to street gutters or ditch.

tions, it was necessary to use the coordinate values that define the locations of features in the watershed. This information was used to define the drainage network and to compute the plane geometry and lengths of routing segments.

Hydrologic response units were defined as polygons representing unique hydrologic soil group and surface characteristics. These polygons might consist of one or more vegetated (pervious) lots or impervious areas (roof tops, streets, parking lots). The polygons also have additional attribute information in the database such as curve number, roughness coefficient, and slope. Using the horizontal *x*- and *y*-coordinates that define the boundaries of polygons, the plane geometry, routing distances, and network ordering could be determined.

In some GIS software, these coordinate values are generally not readily available to the user, but are used by the system for feature manipulations. However, they can be accessed through high level programming within the GIS environment.

The predominant slopes directions in the study area were north-south (*y*). These north-south directions were used as the aspects of the polygons that comprised the hydrologic response units. The endpoints (nodes) of arcs and the change of direction along the arcs that defined the polygons are identified by vertices. The maximum and minimum coordinate values in the east-west (*x*) direction for every polygon were determined by comparing the *x*-coordinate values for every vertex for each arc which defined the polygon. A similar comparison was made to determine the maximum and minimum *y*-coordinates for each polygon in the layer. The maximum lengths of the polygons in the north-south and east-west directions were calculated as the difference between the maximum and minimum values in each direction. In this study, the dimensions of the polygons were determined only in the principal directions (north-south and east-west); however, a similar approach could be used to determine the dimensions in any desired direction. The extreme coordinate values in both principal directions were stored in the feature attribute table of the arc and polygon layers for the watershed.

Algorithms were also written to extract the coordinates of the inlets and junctions of the storm drain network. The inlets and junctions were represented as nodes in the storm drain network layers, and coordinate values were stored in the feature attribute table.

The coordinate values were used to define the stream network ordering system and identify which polygons (or response units) would contribute flow to specific inlets. Figures 1 and 2 show how runoff from each surface polygon was combined at the nearest inlet and the upstream flow for subsequent routing to the block outlet. A series of programs was written in the GIS environment to determine which collection of polygons would contribute to the flow at a particular inlet. These programs were used to extract or calculate the attributes required to determine the discharge at the inlets and outlet.

To start the procedure, the desired inlet is specified as the outflow point, the nearest upstream inlet is identified by the program, and the coordinate values of both inlets are extracted. The identification of the inlets also allows the attributes associated with the connecting storm drain segment to be extracted from the database. Hydrologic response units represented by polygons whose boundaries are defined by coordinate values between those of the inlets are considered to contribute to the flow arriving at the downstream inlet. The next inlet upstream is then identified by the program and the procedure is repeated. The result of the above procedure is to identify the inlet and group all of the polygons contributing to that inlet and their physical attributes. The succession of inlets and their associated polygons determine the hydrologic schematic, or drainage pattern, of the urban watershed.

Calculation of Flow Lengths

Based on the coordinate values of the receiving inlet and the boundaries of the polygons, the overland flow and gutter lengths were calculated for each polygon. The maximum flow length was calculated as the maximum length of the individual polygon in the direction of flow plus any additional overland distance the water from the polygon has to travel to reach the gutter. The gutter flow length was calculated as the distance the water must travel after it entered the gutter to reach the receiving inlet downstream. This process was repeated for every polygon which contributed to the flow at the downstream inlet.

Figure 5 can be used to illustrate this procedure. The maximum flow length of a polygon was calculated based on whether or not the polygon was directly adjacent to the street gutter or ditch. If it was directly adjacent, the flow length was calculated as the difference between the polygon maximum and minimum *y*-coordinate values. If the response area was not directly adjacent to the street, the flow length was calculated with respect to the location of the street gutter and the downstream inlet. Referring to Figure 5, the maximum length for such a polygon would be calculated as the difference between the polygon maximum and minimum *y*-coordinate values, [**Y(4)** − **Y(1)**], plus the overland routing distance to the gutter, i.e., the difference between the polygon maximum *y*-coordinate value and the downstream inlet *y*-coordinate, [**Y(6)** − **Y(4)**]. This is based on the assumption of equality between the *y*-coordinate values of points **7** and **6** on Figure 5. Alternatively, the coordinates of point **7** can be determined and used instead of the coordinates of point **6**. This procedure allows for the two separate flow distances which make up the path from the

TABLE 3. CHARACTERISTICS OF SURFACE POLYGONS AND GUTTER CONNECTING TO THE NEAREST INLET.

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-99999
17 626553.654 200737.564
42 PER 33.429 0.0014 0.1 80 0.635 28.575 12.405
29.474 0.002 0.05 0.0 1.0 TRIANG
43 IMP 32.931 0.001 0.010 98.000 0.635 28.575 7.011
5.979 0.002 0.05 0.0 1.0 TRIANG
44 PER 32.293 0.0034 0.100 74.000 2.540 57.150 20.816
76.872 0.002 0.05 0.0 1.0 TRIANG
45 IMP 32.162 0.0014 0.010 98.000 0.635 28.575 10.863
30.435 0.002 0.05 0.0 1.0 TRIANG
47 PER 31.727 0.0018 0.100 80.000 0.635 28.575 3.641
38.196 0.002 0.05 0.0 1.0 TRIANG
48 IMP 30.987 0.0033 0.010 98.000 2.540 57.150 8.845
72.302 0.002 0.05 0.0 1.0 TRIANG
60 PER 11.729 0.002 0.100 74.000 2.540 57.150 1.371
38.584 0.002 0.05 0.0 1.0 TRIANG
-99999
18 626449.257 200732.496
54 IMP 20.344 0.0032 0.01 98 2.540 57.150 7.019
10.222 0.002 0.05 0.0 1.0 TRIANG
-99999
```

Inlet Separation Code

Inlet
- Number
- x-coordinate (m)
- y-coordinate (m)

Polygon
- Number
- Pervious(PER)/Impervious (IMP)
- Flowlength (m)
- Slope
- Roughness Coeificient
- Curve Number
- Hydraulic Conductivity (mm/hr)
- Soilwater Storage (mm)
- Equivalent Width (m)

Gutter or Ditch
- Length (m)
- Slope
- Routhness Coefficient
- Width or Diameter (cm)
- Side Slope
- Shape

polygon to the gutter to be assigned different characteristics (slope and roughness) if desired. Finally, the routing distance in the gutter or ditch (point **7** to point **6**) is given by the difference between the polygon maximum x-coordinate and the inlet x-coordinate values, i.e., $[\mathbf{X(6)} - \mathbf{X(3)}]$. The width of the polygon (point **4** to point **3**) is taken into account in the overland flow routing scheme from the polygon. Note that the calculation of these distances does not depend on the shape of the polygon being rectangular as in Figure 5, because the coordinate values of all the vertices are available. However, because the predominant slope in this watershed was in the north-south direction, the above approach was used. A similar calculation can be performed along any direction of slope for each polygon.

GIS Manipulation Results

One primary focus of this study was the demonstration of an approach for interfacing a GIS with a hydrologic model. A portion of the data that resulted from the approach described is given in Tables 3 and 4. The data for the surface polygons and storm drains that resulted from the GIS manipulations are written to separate files that provide the interface between the GIS and the hydrologic model. The succession of inlets and their associated response units (polygons) constitute the drainage network or modeling schematic of the watershed.

The identification of the inlet also allowed the relevant storm drains to be identified and their attributes to be ex-

TABLE 4. CHARACTERISTICS OF STORM-DRAIN CONNECTING TWO SUCCESSIVE INLETS.

Previous Inlet Number	Current Inlet Number	ARC Number	Length (m)	Slope	Roughness Coefficient	Width or Diameter (cm)	Side Slope	Shape
17	18	15	104.519	0.0016251710057	0.015	30.48	0	CIRC
18	19	16	11.587	0.0032503420114	0.015	30.48	0	CIRC
19	20	17	17.886	0.0032503420114	0.015	30.48	0	CIRC

Storm Drain

tracted. Typical values of calibration parameters such as Manning roughness coefficients and SCS curve numbers were taken from the literature. All other data needed to run the model were obtained from the physical database contained within the GIS.

The hydraulic routing programs read the output files and use the inlet numbers for the storm drains to guide the modeling to the outflow point. This approach can be used for every street block in the watershed. Blocks are joined together by identification of the storm drain segment which connects them. Therefore, the data that resulted from the manipulation of the GIS database plays a critical function in this approach for coupling the GIS to a hydrologic model.

Hydrologic Modeling

The final output files from the GIS, as shown in Tables 3 and 4, function as the input files to the hydrologic modeling programs. The hydrologic model consists of three components: a simple water balance routine to account for soil moisture, an overland flow routing component, and a routine for gutter or storm sewer routing. All of these programs are written in the C language. The volume of direct runoff from a response unit is determined from the water balance routine, which is based on the SCS curve number procedure (USDA, 1986). Soil moisture accounting in the upper layer of the soil horizon is estimated using infiltration (determined from the curve number) as the inflow and gravitational seepage (determined from the saturated hydraulic conductivity) as the outflow. Direct runoff occurs either when the rainfall intensity exceeds the infiltration capacity of the soil or the soil layer becomes saturated. This procedure is described fully by Greene and Cruise (1995).

The direct runoff from each response area was routed to the street gutter or ditch using an overland flow routine. The overland flow routine was based on the kinematic wave approximation to the one-dimensional shallow water flow equations (Singh, 1992). In this approximation, the friction slope is assumed equal to the bed slope, thus reducing the momentum equation to a simple form of the Manning resistance formula. The momentum (Manning) and continuity equations are solved by a finite difference technique. The procedure used in the U.S. Army Corps of Engineers HEC-1 program (USACOE, 1990) for the solution of these equations is adopted here. Gutter and storm sewer routings are performed in the same manner, also using the finite difference formulation given in the HEC-1 model.

Hydrologic Modeling Results

A full description of the hydrologic functions of the system, together with responses and sensitivity analyses are given by Greene and Cruise (1995). Here, our only purpose is to show that the system results in a reasonable output when applied to a typical area in the watershed.

Figure 4 shows a typical two-block area of the upper Ward Creek watershed. Figure 6 shows the storm drain network for this area. The two blocks are joined together in the system by the identification of the storm drain connecting inlets 26 and 31 in Figure 6. The data shown in Tables 3 and 4 are the output from the GIS for a portion of this area (inlets 17 and 18). The complex hypothetical rainfall pattern applied to this area and the outflow response from the system is shown in Figure 7. The hydrograph shown in the Figure 7 represents the system response predicted at the outlet of the entire two block area (inlet No. 34; Figure 6).

The hydrograph shown in Figure 7 appears to represent a reasonable response for this two-block area (total area 2.5 hectares). The total volume of runoff in the hydrograph matches the volume of direct runoff from the hypothetical rainstorm, the peak magnitudes appear reasonable, and the shape of the hydrograph reflects the shape of the rainstorm

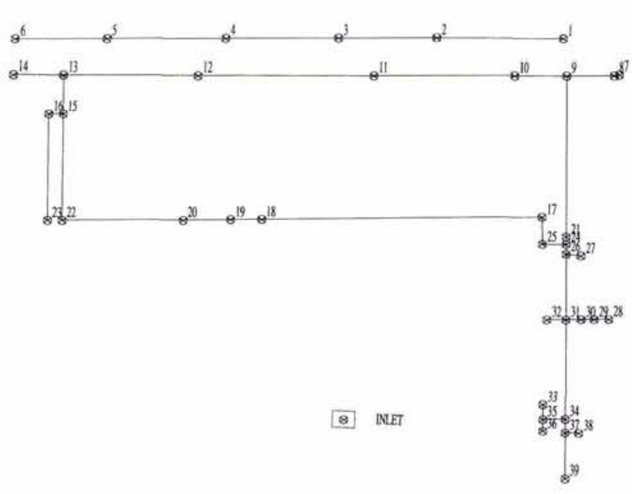

Figure 6. Drainage network for the area shown in Figure 4.

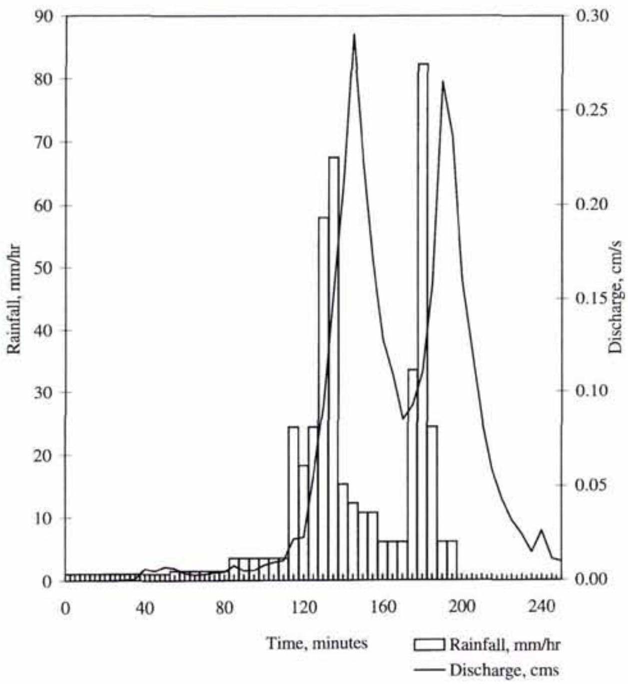

Figure 7. Hypothetical rainfall event and hydrologic simulation results for the two-block area.

shown in Figure 7. Therefore, it appears that the GIS/Hydrologic Modeling system results in physically plausible responses. Additional blocks can be joined to the model through the identification of connecting storm drains until the entire watershed is completed.

Conclusions

A GIS/Hydrologic Modeling system has been described which represents the physical properties of an urban watershed more realistically than has previously been accomplished. The ARC/INFO GIS performs all topological functions and data assignments required to build a preliminary database necessary for hydrologic modeling. However, additional programming was required in order to interface the GIS with the model in terms of definition of the hydrologic network and calculation of plane geometry and routing distances necessary for distributed watershed modeling. The resulting system is a fully integrated GIS/Distributed Watershed Model which requires no human input once the initial raw data layers (topography, soils, land use, etc.) are geocoded. The system performs all relevant computations at scales and levels of detail not accomplished in any previous effort.

Hydrologic simulations with the system show that it does respond with physically plausible results. It is now possible to use the system to investigate the relative effects of spatial heterogeneity and scale differences in urban environments. The ability to analyze spatial impacts at a variety of scales is one of the most attractive features of the system. Impacts of land-use changes within an urban watershed can be evaluated at the polygon, block, multiblock, or basin scale.

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