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Hydrologic Modelling With a Spatial Database.

Richard Gilbert Greene

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Hydrologic modelling with a spatial database

Greene, Richard Gilbert, Ph.D.
The Louisiana State University and Agricultural and Mechanical Col., 1993
HYDROLOGIC MODELLING WITH A SPATIAL DATABASE

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
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requirements for the degree of
Doctor of Philosophy

in

The Department of Civil Engineering

by

Richard Gilbert Greene
B.S., The Ohio State University, 1985
M.S., The Ohio State University, 1987
December 1993
DEDICATION

To my parents,

Nedd Aubrey and Eileen Christina Greene,

my wife, Meredith, and daughters, Giselle and Kristen,

for their sacrifices made over the years.

This dissertation is a manifestation of their love and encouragement.
ACKNOWLEDGMENTS

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ABSTRACT

Hydrologic modelling can be enhanced and improved through the utilization of a Geographic Information System (GIS). Information can be stored and analyzed by the tools available within a GIS to create a spatial database that realistically represents a watershed for hydrologic modelling. This study presents an approach whereby the data available in the GIS determine the modelling strategy. The soil, topography and land cover data for the watershed were analyzed with the spatial analysis tools of a GIS to determine the hydrologic response areas. The coordinate values that define the locations and boundaries of features in the GIS were used to identify which hydrologic response areas contributed to the flow at a particular inlet and to calculate the flow length for those areas. The coordinate values were also used to identify the storm drain that connected to the next downstream inlet and thereby permitted the discharge to be automatically routed downstream. The discharge was calculated using a modified version of the SCS runoff equations for the calculation of the effective rainfall and the kinematic wave routing formulation. The discharge for each hydrologic response area was combined and routed to determine the total discharge for two drainage areas within the watershed. The effects of spatial and scalar changes on the discharge were also investigated.

The results show that when the resolution of the hydrologic response areas was changed it had very little impact on the discharge at the outlet of the two areas investigated. However, the results also indicated that when all the surfaces that
contributed to the discharge at the inlet became impervious there was an increase in the peak discharge of 63.5% at the inlet and only 2.9% at the outlet. The discharge was also found to be sensitive to the surface roughness coefficient, as the investigation showed that the peak discharge from a pervious surface changed as much as 92.3% when the roughness coefficient was varied between 0.01 and 0.100. It was concluded that the inlet of a drainage network should be the location at which the effects of change on the discharge are evaluated.
INTRODUCTION

Water is one of the Earth's most important resources. It is essential for the existence of living organisms. However, too much water (flood) or too little water (drought) can drastically alter the Earth's environment and the life of its inhabitants. The flood in the upper Mississippi River basin and the drought in the southeastern United States of America in 1993 were an expensive reminder about the importance of water. The damage caused by the flood alone was estimated to be over ten billion dollars (Nasar, 1993).

The original source of water is the oceans, and the process by which water is transported from the oceans to the land and back is known as the hydrologic cycle. The basic components of the hydrologic cycle include precipitation, evaporation, transpiration, infiltration, overland flow, stream flow and groundwater flow. The hydrologic cycle is a closed system, and anything that affects a component of the hydrologic cycle would have an effect on the entire cycle.

For centuries, scientists and engineers have been investigating the various components of the hydrologic cycle in order to better understand the processes that are involved and to manage the water for the production of food and energy. Over the last four decades, this investigation has become more quantitative with the development of computers. The rapid development of computers and computer science has enabled investigators to use complex mathematical models for the representation of the components of the hydrologic cycle. In more recent years, the
tendency has shifted towards using the physical characteristics of the watershed in modelling the components of the hydrologic cycle. With the introduction of Geographic Information Systems (GISs) the potential exists for a further increase in use of physical characteristics of the watershed in hydrologic models.

The development of GISs has tremendously changed the way we acquire and use spatial data. GISs have been applied to a wide cross section of disciplines, including engineering, agriculture, geography, geology, planning, natural resources and marketing. Increasingly, a large number of agencies, both private and public, have been incorporating GIS technology in their operations. Within the field of Civil Engineering, GISs have been used increasingly for the solution of water resources problems. However, a review of the literature indicates that the majority of hydrologic applications of GIS were in rural, agricultural and forested drainage basins (Silfer et al., 1987; Cline et al., 1989; Muzik and Pomeroy, 1990; Stuebe and Johnston, 1990; Sicar et al., 1991). Only a few studies directly used a GIS for hydrologic analysis of an urban area (Grayman et al., 1982, Johnson, 1989; Djokic and Maidment, 1991). Most of these studies used a GIS either to determine parameters for existing hydrologic models or to store and display the physical characteristics of the drainage basin.

The lack of spatial detail in hydrologic models is an obstacle toward a better understanding of existing hydrologic conditions. Most hydrologic models use the lumped parameter approach in modelling the runoff from a drainage basin. The use of the lumped parameter approach ignores the spatial variability that exists within the
drainage basin. The quality of hydrologic models can be significantly improved by including the spatial variation of watershed characteristics in the modelling process.

This research focuses on the development of a tool that incorporates the spatial analysis capabilities of a GIS in the hydrologic analysis of an urban watershed. In particular, the data values that describe the feature attributes of the urban watershed were used directly in the hydrologic model to determine the runoff hydrograph. By directly using the data values that describe the physical characteristics of the drainage basin, it was possible to realistically evaluate what effects any modification of the physical characteristics would have on the runoff hydrograph at any location in the drainage basin. In contrast to other GIS applications for hydrologic analysis, the coordinate values that define the location of features in the database were used in order to include the spatial heterogeneity of the drainage basin in the modelling process. The attribute values in the spatial database were accessed directly as the modelling proceeded from the upstream portion of the drainage basin to the downstream point of interest. A model based on the kinematic wave equations was used for overland and channel routing.

The GIS software selected for this study was the ARC/INFO software (Environmental Systems Research Institute, 1991). The ARC/INFO system was chosen because it contains functions that can be applied to vector data which have a higher resolution than raster data, and the system is widely available. The ARC/INFO software is predominately the GIS of choice for both governmental and private agencies that acquire and use a large quantity of spatial data in their
operations. The Ward Creek watershed, a densely populated urban drainage basin, was chosen to demonstrate the importance of the inclusion of watershed spatial heterogeneity in hydrologic modelling. The total discharge of the Ward Creek watershed could be determined, but that was not the primary reason for its selection. The watershed was chosen because of the availability of the basic data, its reasonable size and the accessibility of the watershed for field observations. The ARC/INFO system was used to create a spatial database of the Ward Creek watershed. The topography, soil, land use, pervious and impervious areas, storm drain, stream channel and street network were geocoded into separate layers, and the attribute information for each feature was added to the database feature attribute tables.

The spatial analysis capabilities of GIS facilitated the inclusion of spatial variation of the watershed in hydrologic modelling. The inclusion of the watershed spatial variation in the modelling permitted a better description of how the spatial variability in watershed characteristics affected the surface runoff throughout the basin.

Spatial data consist of geographic entities which have global properties, parts, and related geographic entities (Shapiro, 1980). Knowledge of geographic entities will improve our understanding of the hydrologic condition of the drainage basin and will result in a better model of the hydrologic processes involved.

GISs provide the necessary tools for the use of spatial data in applications that involve geographic entities. GISs provide the tools needed for storage and analysis of spatial data. An integral part of GISs are software modules that are used for data
input and verification, data storage and database management, data output and presentation, data transformation, and interaction with the user (Burrough, 1986). In addition, GIS can interface with other computer systems for operations that cannot be carried out in the GIS environment.

The overall objectives of this study are to increase our understanding of the behavior of runoff in urban areas and to examine the effects of spatial variability in watershed surface characteristics and rainfall fields on runoff from urban areas. The specific objectives are:

1) To establish a detailed spatial database for an urban watershed.
2) To establish a mechanism for the generation of hydrologic response areas.
3) To develop a hydrologic modelling system for the determination of runoff from the hydrologic response areas by linking the database to a hydrologic model.
4) To evaluate the impact that the spatial variability of the watershed characteristics has on the variability of runoff.
LITERATURE REVIEW

Geographic Information Systems Overview

Spatial databases for hydrologic applications can be developed and manipulated through the utilization of GISs. GISs are computer systems consisting of a set of software tools for efficiently collecting, storing, retrieving, analyzing and displaying spatial data and associated attributes. A GIS has three major components: hardware, software, and a proper organizational context (Burrough, 1986). A proper organizational context refers to the fact that a GIS should not function in isolation, but rather it should be properly integrated as much as possible into the entire operation process of the organization using it. The hardware component of a GIS includes a central processing unit, digitizers and scanners, visual display units, and tape and disk drives. The software component of the GIS includes subsystems or modules for data input and verification, data storage and database management, data output and presentation, data transformation and interaction with the user. The major advantage of a GIS over other database management systems (DBMS) is that it allows for spatial analysis of geographic data. New spatial relationships can be created between map features that result in new map features with new associated attributes. The spatial analysis of geographic data is achieved through the following fundamental spatial operations: topological overlay, buffer generation, feature extraction, feature merging and database operations such as relate and join. Mathematical and logical operations can also be performed on map features and attributes.
Spatial Data Structure

In order to effectively and efficiently use spatial data, the data must be organized according to a particular data structure. The relational data structure has the potential for use in spatial hydrologic analysis. In a relational database, the data are perceived by the user as tables and nothing but tables (Date, 1990). The data in a relational system are stored in records containing a set of attribute values that are grouped together in two-dimensional tables called relations. Haralick and Shapiro defined a relational spatial data structure that can be used with geographic data in both vector and raster format (Shapiro and Haralick, 1978; Haralick and Shapiro, 1979; Haralick, 1980; Shapiro, 1980). The spatial data structure also allows analyses that require inferential reasoning to be done with spatial data. Miller (1985) describes a prototype data structure using the system defined by Haralick and Shapiro for hydrologic applications. The spatial data structure is based on a set of relations that represent geographic entities. A geographic entity has global properties, component parts and related geographic entities. A geographic entity can be a simple point defining a location or polygon(s) representing a city or soils within a particular area.

The ARC/INFO Geographic Information System employs a relational database structure (Environmental Systems Research Institute, 1991). It uses a hybrid data model to support spatial and descriptive information of geographic objects. A hybrid data model is a data model that has the characteristics of both vector and raster data models, making it suitable for storage of spatial and descriptive information about geographic objects in both vector and raster formats. The locational data are stored
in a vector or raster data structure, whereas the corresponding descriptive attributes are stored in tables. In order to maintain the spatial relationship among geographic features, the model explicitly records adjacency information in the tables. Furthermore, the spatial and descriptive data are directly linked which ensures that they are always available for spatial analysis. The use of the hybrid data model for geographic objects results in the model being referred to as the georelational model (Morehouse, 1985). Geographic information are represented using either a vector data model or a raster data model depending upon the type of information to be conveyed to the user and kind of analysis to be performed. For instance, geographic features and analyses that are best defined or described by points, lines and boundaries of areas would be better represented by a vector data model which stores the boundaries as sets of coordinate values. Geographic features and analyses that are best defined or described by continuous surfaces are better represented by a raster data model in which each grid cell is assigned a value to represent each parameter it defines. The raster model is also used to represent points, lines and areas. However, the accuracy with which a feature can be represented in a raster data model is subject to the size of a single cell or picture element (pixel) as the assigned value is assumed to be constant throughout the cell. ARC/INFO uses a coverage to represent vector data and a grid to represent raster data.

ARC/INFO Geographic Information System

ARC/INFO follows the application development or tool box approach for GIS development (Morehouse, 1989). In the toolbox approach geoprocessing operations
operate on geographic objects, in contrast to the spatial DBMS approach where the GIS is considered to be a query processor operating on a spatial database. The data model of ARC/INFO is based on a combination of the topological network approach for locational information and the relational approach for feature attributes (Morehouse, 1989).

ARC/INFO Data Model

A detailed discussion of the ARC/INFO data model can be found in Morehouse (1985). The basic unit of data management in the ARC/INFO data model is the coverage or layer that defines locational and thematic attributes for map features in a given area (Morehouse, 1989). The coverage concept is based on the topological model of geographic information and may contain several types of geographic features such as tic, arc, node, polygon, label point and annotation. These feature classes form the basic vocabulary used to define geographic information in a coverage. Any type of geographic information can be included in coverage simply by combining the various feature classes.

In ARC/INFO, each feature class may have an associated feature attributes table that defines the attributes for all features of that class in the coverage. Each individual feature has an associated record in the feature attribute table. The feature attribute tables are an integral part of the coverage and are processed by ARC for all ARC/INFO commands which affect the coverage. A coverage is defined by a set of
relations that define the geometric, topological and attribute values of the various features in the coverage. Some of the key relations in coverage are:

ARC: (arc#, fnode#, tnode#, lpoly#, rpoly#, xy xy xy)

AAT: (arc#, item-1 ....... item-n)

LAB: (label#, poly#, xy)

PAL: (poly#, arc#, ....... arc#)

PAT: (poly#, item-1 ....... item-n)

The vector and raster data models are the basic types of spatial data models employed by the ARC/INFO. The topological data model is the form of vector data model employed by ARC/INFO as it explicitly records adjacency information in order to maintain the spatial relationship among geographic features. Three topological concepts employed by ARC/INFO allow for connectivity, area definition and contiguity (Environmental Systems Research Institute, 1991). For connectivity, arcs are connected to each other at their nodes; such arcs when they surround an area, define a polygon. Also, by arcs having direction and left and right sides, ARC/INFO employs the topological concept of contiguity. In general, the utilization of topological concepts enables ARC/INFO to be used in applications that require modelling flow through connecting lines in a network, combining polygons with similar characteristics, identifying adjacent features and overlaying adjacent geographic features.
GIS and Hydrology

GIS and Hydrologic Modelling

Hydrologic modelling can be considered to be the simulation of the runoff process as a result of precipitation. Viessman et al. (1989) defined simulation as the mathematical description of the response of a hydrologic water resource system to a series of events during a selected time period. In some cases, it requires the correlation of the amount of rainfall and surface characteristics with the observed runoff at a point along a stream as generally done in the empirical approach to hydrologic modelling. Several attempts have been made to incorporate GIS in hydrologic analyses. These attempts can be grouped into four general categories: (1) calculation of input parameters for existing hydrologic models, (2) mapping and display of hydrologic variables, (3) watershed surface representation, and (4) identification of hydrologic response units. Currently, the majority of the GIS applications to hydrologic analysis fall into the first category in the sense that the main uses for GIS are for the determination of input parameters for the traditional lumped-parameter models (Davis, 1978; Ragan and Fellows, 1980; Hill et al., 1987; Johnson and Dallmann, 1987; Silfer, 1987; Cline et al., 1989; Fisher, 1989; Johnson, 1989; Muzik and Pomeroy, 1990; Stuebe and Johnston, 1990; Bhasker and Devulaplli, 1991; Djokic and Maidment, 1991; Moeller, 1991; Ragan and Kosicki (1991), VanBlargan et al., 1991). For instance, Djokic and Maidment (1991) used a GIS (ARC/INFO) with the rational method to determine whether inlets and pipes can convey 10- and 25-year design flows for an urban drainage basin. The longest overland flow paths were
digitized directly and subsequently combined with a Triangulated Irregular Network (TIN) to calculate the change in elevation along the longest flow path. These parameters were then used in the Hathaway's formula to determine the time of concentration. The watershed area, as needed by the formula, was automatically calculated in ARC/INFO when a polygon was defined. Johnson (1989) used a GIS for the automatic generation of input data for a digital map-based hydrologic modelling system that supports the unit hydrograph, time-area, partial area-variable source and cascade of reservoirs hydrologic models. The topography was defined by color coding elevation contour bands, and a digital terrain model was employed to generate slope and aspect. The percent imperviousness of the watershed was based on a land use classification scheme defined for the watershed. A 90, 70, 50, and 2 percent imperviousness was respectively assigned to commercial, high density residential, low density residential and open space. Cline et al. (1989) and Moeller (1991) used a GIS to determine the input parameters required by the HEC-1 model; Sicar et al. (1991) used GIS to determine time area curves; Ragan and Kosicki (1991) used GIS to define input parameters for the SCS hydrologic models.

The use of GIS by Schoolmaster and Marr (1992), Loucks et al. (1985) and Johnson (1989) fall into the second category. In this category GIS was mainly used for presenting the spatial distribution of hydrologic variables.

Other uses of GIS focus on the use of the GIS for better representation of watershed surfaces through the use of Digital Elevation Models (DEMs) and gridded geographic data. This third category includes studies by Davis (1978), Loucks et al.
(1985), Silfer et al. (1987), Brath et al. (1989), VanBlargan et al. (1990), Sicar et al. (1991), Sasowsky and Gardner (1991), VanBlargan et al. (1991), Smith and Brilly (1992). These attempts used spatial data such as DEMs and gridded geographic data to better represent surface features.

Only a few reported uses of GIS indicated that it was used for the identification of hydrologic response units, and these include studies by Thomsen and Striffler (1980), Vieux (1988) and See et al. (1992). These efforts demonstrate that GIS can be used in hydrologic analyses and at the same time increase the productivity of the user. However, most of these attempts were made in either rural, agricultural, or forested basins, and they simply used the GIS for the generation of the input parameters for existing hydrologic models and followed the same processes as if the analyses were being done manually. A majority of these hydrologic models also ignored the spatial variability in watershed characteristics and used average parameters for their representation.

On the other hand, some attempts have been made to incorporate the spatial variability of watershed characteristics in hydrologic modelling by using the TIN data model for representation of the topography and for data storage (Grayman et al., 1982; Goodrich et al., 1991; Maidment et al., 1989; Cuevas and Palacios, 1989; Silfer et al., 1987). Grayman et al. 1982 used a TIN for storage of data needed by an existing runoff model on a triangular facet basis. Silfer et al. (1987) used a GIS based on the TIN and associated data structures, together with a deterministic, finite difference approach, to model the rainfall-runoff process via overland flow and
interflow. Goodrich et al. (1991) and Maidment et al. (1989) both used the TIN to model surface flow with a finite element approach. The TIN methodology and data structure allowed the physical information of the basin to be conveniently stored or calculated on a facet by facet basis. Similarly, Vieux (1988) used GIS to form hydrologic response areas based on slope on a finite element grid constructed from streamlines of flow and elevation contours. He also employed two-dimensional flow equations to provide a global solution over the entire basin network.

Surface Representation

A key component of hydrologic modelling is the representation of the watershed surface. Topographic attributes of the watershed can be characterized by data in DEMs. The three primary forms of DEM are regular grid data, Triangulated Irregular Network (TIN) and contour string (vector) data. An extensive review of these three data structures, together with applications of terrain analysis methods based on these structures for calculating topographic attributes and terrain-based indices for a variety of hydrological, geomorphological and biological processes, can be found in Moore et al. (1991).

Topographic representation by TIN required fewer points than regular grid DEM or contour DEM. Also, the TIN model provides a continuous surface and defines the spatial or locational relationships of the surface that are necessary conditions required by the terrain for continuity and connectivity (Heil, 1979). A large number of studies have demonstrated that hydrologic parameters such as
drainage networks and areas can be automatically extracted from DEM (Collins, 1975, Collins and Moon, 1981; O’Callaghan and Mark, 1984; Band, 1986; Palacios-Velez and Cuevas-Renaud, 1986; Band, 1989; Qian et al., 1990; Jones et al., 1990; Sasowsky and Gardner, 1991; VanBlargan et al., 1991; Moore and Grayson, 1991). For instance, Jones et al. (1990) demonstrated that the TIN data model can be used to determine watershed boundaries and drainage networks. However, as pointed out by Djokic and Maidment (1991), techniques that permit the automatic delineation of drainage areas from digital surface representation in rural areas would be a very difficult task in urban areas, as the natural paths of storm water flow over the surface are modified by artificial structures such as streets, buildings and storm sewers.

Study Approach

The approach to be taken in this study is to make the GIS an integral part of the entire hydrologic modelling process. The GIS will be used to assign all attributes (such as curve numbers and roughness coefficients) to features throughout the drainage basin. In addition, GIS will be used to create a spatial database that represents the existing watershed as realistically as possible. Hydrologic response areas will be defined using the topological overlay functions within the GIS, using the various basic layers such as topography, soil, imperviousness, and drainage, and their attributes and derivatives. Locational information for these hydrologic response areas will be used to determine which areas contribute to the flow at a particular location. Also, the coordinate values that define each hydrologic area will be used to define the flow
length of those areas. The data values that describe the physical characteristics of these areas will be accessed directly by algorithms written in the GIS environment to extract the information needed to determine the discharge hydrograph at the point of interest. The discharge hydrograph is determined by a hydraulic model based on the kinematic wave equations.
METHODOLOGY

The approaches taken to the study of hydrologic problems can generally be grouped into two categories: (1) the physical approach and (2) the empirical approach. The primary motivation in the physical approach to hydrologic modelling is the studying and understanding of the hydrologic cycle (Singh, 1988). Physical hydrologic modelling normally requires the specification of (a) the governing equations which are based on physical laws such as the laws of conservation of mass and momentum, (b) the geometry of the system (watershed or drainage basin), (c) the input function such as rainfall, and (d) the initial and boundary conditions. Examples of the physical approach are hydrologic models that are based on the kinematic wave theory.

The empirical approach to hydrologic modelling seeks to establish an input-output relationship for a particular system (watershed or drainage basin). The major concerns of this approach are with the system operations, rather than with the system components or the physical laws governing its operations. An example of the empirical approach is the rainfall-runoff relations that relate the rainfall (input) to the runoff hydrograph (output). The rational method is a popular empirical model.

The hydrologic modelling of a watershed with a GIS should include the following steps:

1) Build a spatial database of soils, topography, land use, land cover and drainage network.
2) Perform spatial analysis to generate hydrologic response areas (polygon).

3) Determine the effective rainfall using a technique such as the Soil Conservation Service (SCS) curve number technique and a soil moisture accounting procedure to determine the effective rainfall for every polygon.

4) Route runoff from hydrologic response areas to specific points of interest using a model such as the Kinematic Wave Model for surface runoff and channel routing.

5) Calibrate and verify model results through the use of goodness-of-fit criteria and reliability analyses.

6) Evaluate the impact of watershed spatial variability on runoff by changing the criteria used for the generation of hydrologic response areas and by varying the rainfall fields.

The Spatial Database

In order to accurately simulate the runoff from a watershed as a result of precipitation, the characteristics of the watershed have to be represented as realistically as possible in physically based models. Prior to the development of GIS, the characteristics of a watershed were represented by average parameters in hydrologic models that required calibration with observed runoff data. The requirement for calibration prevented hydrologic models from being used on watersheds or locations that did not have observed runoff data without risking an increase in the uncertainty in the model result. With the development of GIS, it is
now possible to store and analyze large amounts of spatial data that accurately represent a watershed. Studies have shown that the use of GIS in hydrologic simulation can increase productivity (Muzik and Pomeroy, 1990; Ragan and Kosicki, 1991). In addition, the use of GIS should improve our understanding of the basic runoff processes especially as they relate to urban areas.

The Ward Creek Watershed

The urban watershed selected for this study was the upper portion of the Ward Creek watershed. The study drainage area is approximately 4.68 square miles and is located north of Government Street in the city of Baton Rouge, Louisiana. The land use of the area is predominantly mixed residential, with some industrial and commercial areas (Figure 1).

The building of a spatial database for the Ward creek watershed required the tedious task of acquiring and compiling data from various sources. This task was made much more difficult by the fact that none of the data were available in digital form, and the data acquired from the various sources were at different scales and resolutions. Data that are usually available in digital format such as LANDSAT or SPOT images, were considered to be inadequate for the detailed data requirement of this study. Even though it was understood that data of different scales and resolutions may adversely affect the result of any study, for this particular study their effects were considered to be minimal as the range of scales for the basic data used were small (Table 1). All the data obtained were geocoded manually and referenced to the
WARD CREEK WATERSHED LANDUSE
Based on the Florida Land Use/Cover Classification System

- 112 Single family dwellings
- 116 Multi-family dwellings
- 121 Retail and service
- 131 Light industrial
- 161 Educational facilities
- 167 Cemeteries
- 173 Parks and playgrond
- 163 Medical and health care facilities
- 166 Governmental, administrative, and service facilities
- 191 Undeveloped land within urban areas
- 132 Heavy industrial
- 192 Inactive land with street patterns but without structures

Figure 1. Landuse and street network of the upper Ward Creek watershed.
Table 1. Data sources and scales of data for the upper Ward Creek watershed.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography (2ft Contours)</td>
<td>U. S. Corps of Engineers, New Orleans District, LA</td>
<td>1&quot; = 300 ft</td>
</tr>
<tr>
<td>Soil</td>
<td>Soil Survey of East Baton Parish, Louisiana</td>
<td>1:20000</td>
</tr>
<tr>
<td>Landuse</td>
<td>City-Parish Planning Commission of the City of Baton Rouge and the Parish of East Baton Rouge</td>
<td>1&quot; = 400 ft</td>
</tr>
<tr>
<td>1992 Black and White Photo</td>
<td></td>
<td>1&quot; = 500 ft</td>
</tr>
<tr>
<td>1989 NAPP Color Infrared Photo</td>
<td></td>
<td>1: 40000</td>
</tr>
<tr>
<td>Pervious and Impervious Areas</td>
<td>1992 Black and White Photo</td>
<td>1&quot; = 500 ft</td>
</tr>
<tr>
<td>Street Network</td>
<td>City-Parish Planning Commission of the City of Baton Rouge and the Parish of East Baton Rouge</td>
<td>1&quot; = 400 ft</td>
</tr>
<tr>
<td>Street Pavement</td>
<td>1992 Black and White Photo</td>
<td>1&quot; = 500 ft</td>
</tr>
<tr>
<td>Drainage</td>
<td>East Baton Rouge Department of Public Works</td>
<td>1&quot; = 200 ft</td>
</tr>
</tbody>
</table>
Louisiana State Plane Coordinate System. In order to reduce registration error and to provide consistency among the various layers, the same series of control points were used to reference each coverage or layer to the state plane coordinate system. The topography, soil, land use, pervious and impervious areas, storm drain, stream channel and street network were geocoded in separate layers, using the ARC/INFO GIS software to create a spatial database of the upper Ward Creek watershed (Table 1).

The topography was digitized from U. S. Army Corps of Engineers contour maps at a scale of 1 in = 300 ft (Figure 2). These maps had contour intervals of 2 feet and were compiled from aerial photographs at a scale of 1:18000. Table 2 is a portion of the feature attribute table topography coverage. Slope and aspect information were obtained by constructing a TIN from the digitized contours.

The soil information was obtained from the soil survey of East Baton Rouge Parish, published at a scale of 1:20000 (U. S. Department of Agriculture, 1968). Polygons representing unique soil series were digitized from the published maps (Figure 3). The hydrologic soil group and its hydraulic conductivity were included as attributes to each soil series (Figure 4, Table 3). Other soil profile information included in a separate soil attribute table is as follows: soil type, soil depth, soil thickness and available water storage capacity. In a typical soil profile, the soil type consists of silt loam with an intervening layer of silty clay loam. The presence of such a intervening layer will result in a retardation of percolation thereby creating a
Figure 2. Topography of the upper Ward Creek watershed at 2 ft contour interval.
Table 2. A portion of the topographic coverage, WARDTOPO, feature attribute table.

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<th>TNODE#</th>
<th>LPOLY#</th>
<th>RPOLY#</th>
<th>LENGTH</th>
<th>WARDTOPO#</th>
<th>WARDTOPO-ID</th>
<th>ELEVATION</th>
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<td>24</td>
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<td>0</td>
<td>5204.98359</td>
<td>4</td>
<td>54.000</td>
</tr>
</tbody>
</table>
WARD CREEK WATERSHED SOIL SERIES
Source: East Baton Rouge, LA Soil Survey

Deerford-Oliver silt loams, 0 to 1% slopes (DIA)
Jeanerette silt loam (Je)
Made land
Eisen and Lafe silt loams (Es)
Oliver silt loam, 0 to 1% slopes (OIA)
Oliver silt loam, 1 to 3% slopes (OIB)
Calboun silt loam (Cc)
Jeanerette-Frost silt loams (Jt)
Loring silt loam, 1 to 3% slopes (LoB)
Verdun-Deerford silt loams (Ve)
Fred silt loam (Fr)
Fountain silt loam (Fn)

Figure 3. Soil series of soil in the upper Ward Creek watershed.
Figure 4. Hydrologic soil group of the soil series in the upper Ward Creek watershed.
Table 3. A portion of the soil coverage, SOIL, feature attribute table.

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<td>= C</td>
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<td>HYD-CONDUCTIVITY</td>
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<td>SOIL-SERIES</td>
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<td>HYDRO-SOIL-GROUP</td>
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</tr>
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<tr>
<td>SOIL-SERIES</td>
<td>= Cc</td>
</tr>
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<td>= D</td>
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<td>HYD-CONDUCTIVITY</td>
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</tr>
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</tr>
<tr>
<td>SOIL-ID</td>
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<td>SOIL-SERIES</td>
<td>= Je</td>
</tr>
<tr>
<td>HYDRO-SOIL-GROUP</td>
<td>= D</td>
</tr>
<tr>
<td>HYD-CONDUCTIVITY</td>
<td>= 0.025</td>
</tr>
</tbody>
</table>
dynamic storage region in the upper layer of the soil profile. The capacity of the storage region would have a direct effect on the rate of surface runoff.

The street network was obtained from zoning maps of the City of Baton Rouge and Parish of East Baton Rouge Planning Commission (Figure 1). These maps were at a scale of 1 in = 400 ft and were compiled directly from survey plats. The street network was obtained by digitizing each street block as an independent polygon. The street network was supplemented with information from 1992 Black and White aerial photographs acquired at a scale of 1 in = 1000 ft and enlarged to 1 in = 500 ft. A separate layer was obtained for street pavement by digitizing them as polygons from the black and white photographs. The street network from the zoning maps was in some cases a right-of-way for new streets or street expansions.

The impervious and pervious areas, digitized as polygons in a separate layer, were also obtained from the black and white aerial photographs (Figures 5(a) and 5(b)). Table 4 is a portion of the feature attribute table showing a sample of surface characteristics in the watershed. The black and white aerial photographs, together with the zoning maps and 1989 U. S. Geological Survey National Aerial Photography Program (NAPP) color infrared photographs at a scale of 1:40000, were useful in providing additional recent land use information. Impervious surfaces include roads, sidewalks, parking lots and roof of buildings.

The storm drain network was obtained from maps compiled by the city of Baton Rouge Department of Public Works (DPW) at a scale of 1 in. = 200 ft. (Figure 6). Table 5 is a portion of the storm drain attribute table showing the kinds of
Figure 5(a). Pervious and impervious areas in a portion of the upper Ward Creek watershed.
Figure 5(b). Inset in Figure 5(a).
Table 4. A portion of the pervious-impervious coverage, WARDPERV, feature attribute table.

<table>
<thead>
<tr>
<th>AREA</th>
<th>PERIMETER</th>
<th>WARDPERV#</th>
<th>WARDPERV-ID</th>
<th>SURFACE</th>
<th>ROUGHNESS</th>
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<td>42215.80044</td>
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<td>763</td>
<td>IMP</td>
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<td>28460.77828</td>
<td>920.08716</td>
<td>5</td>
<td>826</td>
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<td>245.78666</td>
<td>6</td>
<td>768</td>
<td>PER</td>
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<tr>
<td>1356.66179</td>
<td>152.13700</td>
<td>7</td>
<td>795</td>
<td>IMP</td>
<td>0.010</td>
</tr>
</tbody>
</table>
Figure 6. Drainage network of the upper Ward Creek watershed.
Table 5. A portion of the storm drain, STORMDRAIN2, feature attribute coverage table.

<table>
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<tr>
<th>346</th>
<th>347</th>
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<tbody>
<tr>
<td>FNODE# = 352</td>
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</tr>
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<td>SIDESLOPEV = 0.000</td>
<td>SIDESLOPEV = 0.000</td>
</tr>
</tbody>
</table>
information included in the database for the storm drain network. These maps were compiled from records on file with that department. However, the records of storm drain maps were incomplete, and it was necessary to supplement that information with actual ground surface observations. That is, the existence or non-existence of inlets or storm drains was identified and verified through field inspection. The dimensions and other parameters that characterized the identified inlets or storm drains were subsequently obtained from DPW. Streets which had curbs were distinguished from streets without curb through visual inspection.

The traverse of Ward Creek was obtained from a combination of information available on the aerial photographs, zoning maps, and storm drain maps. Cross-section information for Ward Creek was obtained from project maps on file with DPW.

Utilization of the Spatial Database

The ARC/INFO GIS has a large number of functions or commands that can operate on spatial data. These functions provide the means whereby the spatial database can be manipulated into a preliminary form suitable for hydrologic applications. Functions can be used to assign feature attribute values or to create new features with the appropriate attributes suitable for hydrologic analysis. These functions can be applied over an entire coverage or on a selected set of coverages. An example of such a feature attribute is the Soil Conservation Soil (SCS) curve number (cn). The SCS curve number is a function of a soil hydrologic soil group and
the imperviousness of the watershed. The overlay functions in a GIS will permit the rapid combination of the soil layer with the surface layer to create a layer that is based on curve numbers or to assign curve numbers to existing features. Through the utilizations of these functions, a realistic preliminary database can be created for hydrologic modelling.

The ARC/INFO commands "select" and "calculate" were used to assign values to features in the database. For example, to assign a roughness value to a surface feature the commands are used as follows:

```
select surface = 'PER'
calculate roughness = 0.100
select surface = 'IMP'
calculate roughness = 0.010
```

The roughness values used for this study were obtained from King (1963). Since runoff from the surface is dependent on the surface and soil characteristics, the soil layer was overlayed on the surface coverage so that the soil composition of the surface could be determined. This type of operation was facilitated in ARC/INFO by three topological overlay operations: union, identity and intersect. The identity operation with the nojoin option was used to overlay the surface layer with the soil layer. The identity topological overlay operation retains all the input features in the resulting output, as opposed to the union topological operation which retains both the input and overlay features in the output. The nojoin option was preferred, as it reduced the size of the output coverage attribute table by only including the feature's internal number
from the input and overlayed coverage feature attribute table. The soil characteristics were connected to the surface feature through a series of related relations. The "identity" command could be used as follows:

Identity wardperv soil wardpervsoil poly # nojoin

where wardperv is the input coverage, soil is the overlay coverage, wardpervsoil is the output coverage to be created, poly is the feature class polygon to be used, and # is the default value for the minimum distance between coordinates in the output coverage. Figures 7(a) and 7(b) are a portion of the resulting coverage from the above "identity" operation, and Table 6 is a portion of its feature attribute table. As shown in Table 6, the feature attribute table contains the items SOIL# and WARDPERV#. These items enable the table to act as a lookup table between the soil coverage, SOIL, and the pervious-impervious coverage, WARDPERV.

The output coverage feature attribute table, wardpervsoil.pat, is related to the surface feature attribute table, wardperv.pat, and the soil feature attribute table, soil.pat, by the relate relations shown in Table 7. The relations in Table 7 can be used to access item values needed for analysis or to assign values based on some specific criteria. For instance, the Soil Conservation Service curve number is dependent on the antecedent moisture conditions, land use or land cover, and the hydrologic soil group. Therefore, selections of the following form can be made to assign a particular curve number:

select wpsoil//surface eq 'PER' and wpsoil2//hydro-soil-group eq 'D'

calculate cn2 = 80
Figure 7(a). A portion of the surface and soil overlay coverage.
Figure 7(b). Inset of Figure 7(a).
Table 6. A portion of the soil and surface overlay coverage, WARDPERVSOIL, feature attribute table.

<table>
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Table 7. Relate relations for soil and surface feature attribute tables.

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<td>SOIL#</td>
<td>soil#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPROP2</td>
<td>soil.prop</td>
<td>info</td>
<td>SOIL-SERIES</td>
<td>soil-series</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
</tbody>
</table>
sel wpsoil//surface eq 'IMP'
calculate cn2 = 98

select wpsoil//surface eq 'PER' and wpsoil2//hydro-soil-group eq 'C'
calculate cn2 = 74

where wpsoil, wpsoil2 are names of relate relations, while surface and hydro-soil-group are feature attributes with 'PER' and 'D' as attribute values. The above statements will assign all coverage features that have the combination of soil and surface characteristics the particular curve number value. For example, all areas in the database that have a hydrologic soil group of 'C', a surface covered with grass, and are considered to be pervious will be assigned a curve number of 74. Similarly, areas that are impervious will be assigned a value of 98 (Table 8).

The information in the database can also be listed or accessed for analysis. The following commands list the soil series and the soil water storage capacity in horizon A:

    select all

    list warperv# spropl//soil-series spropl//sprop2//upper-limit

Table 9 is a portion of the results of the above two sequences of commands, and Table 10 is a portion of the soil properties table, SOIL.PROP. The values in the selected set can be accessed in ARC/INFO using a programming concept known as cursor processing. An example of access by cursor is as follows:

    &setvariable cn2 = %:edit.cn2%
    &setvariable upperlimit = %:edit.sprop1//sprop2//upper-limit%
Table 8. A portion of the soil and surface overlay coverage, WARDPERVSOIL, feature attribute table showing polygon attributes.

<table>
<thead>
<tr>
<th>AREA</th>
<th>PERIMETER</th>
<th>WARDPERVSOIL#</th>
<th>WARDPERVSOIL-ID</th>
<th>WARDPerv#</th>
<th>SOIL#</th>
<th>CN2</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>235.28710</td>
<td>108.93109</td>
<td>21</td>
<td>20</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80.000</td>
</tr>
<tr>
<td>21</td>
<td>1765.31116</td>
<td>168.41541</td>
<td>22</td>
<td>21</td>
<td>2</td>
<td>98.000</td>
</tr>
<tr>
<td>22</td>
<td>188.80537</td>
<td>56.10628</td>
<td>23</td>
<td>22</td>
<td>2</td>
<td>74.000</td>
</tr>
</tbody>
</table>
Table 9. Soil series and soil water storage capacity for selected surface polygons.

<table>
<thead>
<tr>
<th>Record</th>
<th>WARDPERV#</th>
<th>SPROP1//SOIL-SERIES</th>
<th>SPROP1//SPROP2//UPPER-LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>14</td>
<td>15</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>16</td>
<td>17</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>17</td>
<td>18</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>18</td>
<td>19</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>19</td>
<td>20</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>20</td>
<td>17</td>
<td>Je</td>
<td>1.125</td>
</tr>
<tr>
<td>21</td>
<td>21</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>22</td>
<td>22</td>
<td>DFA</td>
<td>2.250</td>
</tr>
<tr>
<td>23</td>
<td>23</td>
<td>Je</td>
<td>1.125</td>
</tr>
<tr>
<td>24</td>
<td>24</td>
<td>DFA</td>
<td>2.250</td>
</tr>
</tbody>
</table>
Table 10. A portion of the soil properties table, SOIL.PROP.

<table>
<thead>
<tr>
<th></th>
<th>SOIL-SERIES</th>
<th>SOIL-TYPE</th>
<th>DEPTH</th>
<th>STORAGE-CAPACITY</th>
<th>THICKNESS</th>
<th>UPPER-LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cc</td>
<td>SILT LOAM</td>
<td>12.000</td>
<td>0.225</td>
<td>12.000</td>
<td>2.700</td>
</tr>
<tr>
<td>2</td>
<td>DfA</td>
<td>SILT LOAM</td>
<td>10.000</td>
<td>0.225</td>
<td>10.000</td>
<td>2.250</td>
</tr>
<tr>
<td>3</td>
<td>Es</td>
<td>SILT LOAM</td>
<td>6.000</td>
<td>0.225</td>
<td>6.000</td>
<td>1.350</td>
</tr>
<tr>
<td>4</td>
<td>Fn</td>
<td>SILT LOAM</td>
<td>10.000</td>
<td>0.225</td>
<td>10.000</td>
<td>2.250</td>
</tr>
<tr>
<td>5</td>
<td>Fr</td>
<td>SILT LOAM</td>
<td>9.000</td>
<td>0.225</td>
<td>9.000</td>
<td>2.025</td>
</tr>
</tbody>
</table>
The above statements are ARC Macro Language (AML) statements that allow the value of cn2 and upperlimit to be used in numerical computation.

A similar approach can be undertaken to access and use slope-related information. The contour layer was used to build a TIN using the "createtin" command in ARC/INFO. An example of the "createtin" command is as follows:

```
createtin tin13 100 # # wardtopo
```

```
cover wardtopo line elevation mass
```

The TIN was transformed into a 2-dimensional layer in order to be used with the other layers. The ARC/INFO command "tinarc" was used for this transformation, and the results provided information on slope and aspect for each triangular facet. An example of use of this command is shown below:

```
tinarc tin13 wardtin13 poly wardtin13 poly percent
```

The results shown in Table 11 are a portion of the resulting coverage, wardtin13, feature attribute table.

The surface layer is overlayed with the tin layer to access the slope for each surface area. The topological overlay command "identity" with the nojoin option, was used for this transformation and a portion of the result is shown in Figures 8(a) and 8(b). The resulting feature attribute table (Table 12) can be used as a lookup table to relate the surface layer attribute table to the slope information in the TIN layer attribute table (Table 11). Depending on the requirements of the investigation, information could now be obtained for each resulting unit area based on a unique soil type, slope and surface characteristics. Table 13 shows the slope results for each
Table 11. A portion of the TIN coverage, WARDTIN13, feature attribute table.

<table>
<thead>
<tr>
<th>AREA</th>
<th>PERIMETER</th>
<th>WARDTIN13#</th>
<th>WARDTIN13-ID</th>
<th>PERCENT_SLOPE</th>
<th>ASPECT</th>
<th>SAREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>6877</td>
<td>30786.52231</td>
<td>6878</td>
<td>6877</td>
<td>0.414</td>
<td>125.273</td>
<td>30786.78637</td>
</tr>
<tr>
<td>6878</td>
<td>213491.37849</td>
<td>6879</td>
<td>6878</td>
<td>0.374</td>
<td>132.715</td>
<td>213492.87460</td>
</tr>
<tr>
<td>6879</td>
<td>32444.97008</td>
<td>6880</td>
<td>6879</td>
<td>0.312</td>
<td>71.629</td>
<td>32445.12784</td>
</tr>
<tr>
<td>6880</td>
<td>32634.78485</td>
<td>6881</td>
<td>6880</td>
<td>0.325</td>
<td>106.358</td>
<td>32634.95724</td>
</tr>
</tbody>
</table>
Figure 8(a). A portion of the surface, soil, TIN overlay coverage.
Figure 8(b). Inset of Figure 8(a).
Table 12. A portion of the soil, surface, and TIN overlay coverage, WPERVERSOILTIN, feature attribute table.

<table>
<thead>
<tr>
<th>Year</th>
<th>AREA</th>
<th>PERIMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>249.47852</td>
<td>73.74618</td>
</tr>
<tr>
<td></td>
<td>1978</td>
<td>1294.54958</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>2067.57303</td>
</tr>
<tr>
<td></td>
<td>1980</td>
<td>3129.84680</td>
</tr>
<tr>
<td></td>
<td>1981</td>
<td>268.19827</td>
</tr>
<tr>
<td></td>
<td>1980</td>
<td>268.19827</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>268.19827</td>
</tr>
<tr>
<td></td>
<td>1978</td>
<td>268.19827</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>268.19827</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WARDPERVSOIL#</td>
<td>708</td>
<td>708</td>
<td>709</td>
<td>710</td>
</tr>
<tr>
<td>WARDTIN13#</td>
<td>6877</td>
<td>6878</td>
<td>6878</td>
<td>6878</td>
</tr>
</tbody>
</table>
Table 13. Percent slope for selected polygons.

<table>
<thead>
<tr>
<th>Record</th>
<th>WARDPERVSOIL#</th>
<th>WPSTINSLOPE/PERCENT_SLOPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>708</td>
<td>0.000</td>
</tr>
<tr>
<td>1977</td>
<td>708</td>
<td>0.509</td>
</tr>
<tr>
<td>1978</td>
<td>708</td>
<td>0.414</td>
</tr>
<tr>
<td>1979</td>
<td>709</td>
<td>0.414</td>
</tr>
<tr>
<td>1980</td>
<td>710</td>
<td>0.414</td>
</tr>
<tr>
<td>1983</td>
<td>710</td>
<td>0.374</td>
</tr>
<tr>
<td>1984</td>
<td>712</td>
<td>0.374</td>
</tr>
<tr>
<td>1988</td>
<td>714</td>
<td>0.374</td>
</tr>
<tr>
<td>1991</td>
<td>717</td>
<td>0.374</td>
</tr>
<tr>
<td>1996</td>
<td>718</td>
<td>0.374</td>
</tr>
<tr>
<td>1998</td>
<td>720</td>
<td>0.374</td>
</tr>
<tr>
<td>2003</td>
<td>708</td>
<td>0.000</td>
</tr>
<tr>
<td>2004</td>
<td>708</td>
<td>0.000</td>
</tr>
<tr>
<td>2049</td>
<td>709</td>
<td>0.000</td>
</tr>
<tr>
<td>2055</td>
<td>742</td>
<td>0.000</td>
</tr>
<tr>
<td>2058</td>
<td>745</td>
<td>0.000</td>
</tr>
<tr>
<td>2059</td>
<td>745</td>
<td>0.414</td>
</tr>
<tr>
<td>2061</td>
<td>746</td>
<td>0.374</td>
</tr>
<tr>
<td>2063</td>
<td>747</td>
<td>0.414</td>
</tr>
<tr>
<td>2064</td>
<td>748</td>
<td>0.374</td>
</tr>
<tr>
<td>2077</td>
<td>752</td>
<td>0.414</td>
</tr>
<tr>
<td>2078</td>
<td>753</td>
<td>0.414</td>
</tr>
<tr>
<td>2080</td>
<td>752</td>
<td>0.374</td>
</tr>
<tr>
<td>2081</td>
<td>755</td>
<td>0.374</td>
</tr>
<tr>
<td>2086</td>
<td>710</td>
<td>0.374</td>
</tr>
<tr>
<td>2087</td>
<td>753</td>
<td>0.374</td>
</tr>
<tr>
<td>2091</td>
<td>746</td>
<td>0.312</td>
</tr>
<tr>
<td>2095</td>
<td>710</td>
<td>0.312</td>
</tr>
<tr>
<td>2096</td>
<td>710</td>
<td>0.374</td>
</tr>
<tr>
<td>2097</td>
<td>746</td>
<td>0.312</td>
</tr>
<tr>
<td>2098</td>
<td>710</td>
<td>0.312</td>
</tr>
<tr>
<td>2099</td>
<td>760</td>
<td>0.312</td>
</tr>
</tbody>
</table>
polygon as a result of the overlay operation with the TIN coverage. This table indicates that the operation resulted in multiple slopes for each polygon; these can be used if the polygon is being divided into smaller sections based on slope or if the slope profile is needed.

In this study, the average slope of the polygon was considered to be sufficient for the intended hydrologic analysis, and that was used instead of the slope profile. The ARC/INFO command "statistics" was used to create a table with average slope for every unique soil and surface characteristic (Table 14). Polygons that had a zero slope were assigned a one-tenth percent slope during computations. The soil and surface layer feature attribute table was connected to the average slope table by a number of relate relations as shown in Table 15. The following is an example of a sequence of commands that could be used to access this information:

```
select wardpervsoil# ge 708 and wardpervsoil le 711
list wardpervsoil# cn2 sprop1//hyd-conductivity sprop1//sprop2//upper-limit ~
    wpslope//mean-percent_slo
```

The results of the above sequence of commands are in Table 16. The following four statements below would access the database and allow the values of cn2, hydraulic conductivity, upperlimit and percent slope to be used in numerical computations that requires them.

```
&setvariable cn2 = %:edit.cn2%
&setvariable hydconductivity = %:edit.sprop1//hyd-conductivity%
```
Table 14. Average percent slope for selected polygons.

<table>
<thead>
<tr>
<th>Record</th>
<th>WARDPERVSOCIL#</th>
<th>FREQUENCY</th>
<th>MEAN-PERCENT_SLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>26</td>
<td>6</td>
<td>0.000000</td>
</tr>
<tr>
<td>26</td>
<td>27</td>
<td>8</td>
<td>0.000000</td>
</tr>
<tr>
<td>27</td>
<td>28</td>
<td>3</td>
<td>0.000000</td>
</tr>
<tr>
<td>28</td>
<td>29</td>
<td>4</td>
<td>0.000000</td>
</tr>
<tr>
<td>29</td>
<td>30</td>
<td>6</td>
<td>0.027067</td>
</tr>
<tr>
<td>30</td>
<td>31</td>
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<td>0.077495</td>
</tr>
<tr>
<td>31</td>
<td>32</td>
<td>3</td>
<td>0.000000</td>
</tr>
<tr>
<td>32</td>
<td>33</td>
<td>1</td>
<td>0.162402</td>
</tr>
<tr>
<td>33</td>
<td>34</td>
<td>2</td>
<td>0.081201</td>
</tr>
<tr>
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<td>0.000000</td>
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<td>37</td>
<td>3</td>
<td>0.054134</td>
</tr>
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<td>36</td>
<td>38</td>
<td>3</td>
<td>0.167504</td>
</tr>
<tr>
<td>37</td>
<td>39</td>
<td>1</td>
<td>0.192533</td>
</tr>
<tr>
<td>38</td>
<td>40</td>
<td>3</td>
<td>0.167504</td>
</tr>
<tr>
<td>39</td>
<td>41</td>
<td>1</td>
<td>0.162402</td>
</tr>
<tr>
<td>40</td>
<td>42</td>
<td>10</td>
<td>0.057760</td>
</tr>
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<td>41</td>
<td>43</td>
<td>2</td>
<td>0.096267</td>
</tr>
<tr>
<td>42</td>
<td>44</td>
<td>2</td>
<td>0.000000</td>
</tr>
<tr>
<td>43</td>
<td>45</td>
<td>1</td>
<td>0.000000</td>
</tr>
<tr>
<td>44</td>
<td>46</td>
<td>2</td>
<td>0.000000</td>
</tr>
<tr>
<td>45</td>
<td>47</td>
<td>1</td>
<td>0.192533</td>
</tr>
<tr>
<td>46</td>
<td>48</td>
<td>1</td>
<td>0.162402</td>
</tr>
<tr>
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<td>1</td>
<td>0.000000</td>
</tr>
<tr>
<td>48</td>
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<td>1</td>
<td>0.192533</td>
</tr>
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<td>51</td>
<td>14</td>
<td>0.077994</td>
</tr>
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<td>52</td>
<td>2</td>
<td>0.096267</td>
</tr>
<tr>
<td>51</td>
<td>53</td>
<td>1</td>
<td>0.000000</td>
</tr>
<tr>
<td>52</td>
<td>54</td>
<td>1</td>
<td>0.162402</td>
</tr>
</tbody>
</table>
Table 15. Relate relations for soil, surface, and TIN feature attribute tables.

<table>
<thead>
<tr>
<th>Relate Name</th>
<th>Table:</th>
<th>Database:</th>
<th>Item:</th>
<th>Column:</th>
<th>Relate Type</th>
<th>Relate Access</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPSTINSL</td>
<td>WARDTIN13.PAT</td>
<td>INFO</td>
<td>WARDTIN13#</td>
<td>WARDTIN13#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
<tr>
<td>WPSLOPE</td>
<td>wps-slope</td>
<td>info</td>
<td>WARDPERVSOIL#</td>
<td>WARDPERVSOIL#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
<tr>
<td>STDTINSL</td>
<td>WARDTIN13.PAT</td>
<td>INFO</td>
<td>WARDTIN13#</td>
<td>WARDTIN13#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
<tr>
<td>STORMSLO</td>
<td>SD-SLOPE</td>
<td>INFO</td>
<td>STORMDRAIN2#</td>
<td>STORMDRAIN2#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
<tr>
<td>PAVESLOP</td>
<td>WARDTIN13.PAT</td>
<td>INFO</td>
<td>WARDTIN13#</td>
<td>WARDTIN13#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
<tr>
<td>PAVESURF</td>
<td>PAVEMENT.PAT</td>
<td>INFO</td>
<td>PAVEMENT#</td>
<td>PAVEMENT#</td>
<td>LINEAR</td>
<td>RO</td>
</tr>
</tbody>
</table>
Table 16. Curve number, hydraulic conductivity, and soil storage capacity for selected polygons.

<table>
<thead>
<tr>
<th>WARDPERVSOIL#</th>
<th>CN2</th>
<th>SPROP1//HYD-CONDUCTIVITY</th>
<th>SPROP1//SPROP2//UPPER-LIMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>707</td>
<td>98.000</td>
<td>0.025</td>
<td>1.125</td>
</tr>
<tr>
<td>708</td>
<td>80.000</td>
<td>0.025</td>
<td>1.125</td>
</tr>
<tr>
<td>709</td>
<td>74.000</td>
<td>0.100</td>
<td>2.250</td>
</tr>
<tr>
<td>710</td>
<td>98.000</td>
<td>0.100</td>
<td>2.250</td>
</tr>
<tr>
<td>711</td>
<td>74.000</td>
<td>0.100</td>
<td>2.250</td>
</tr>
</tbody>
</table>
A similar approach was followed to acquire slope information for the storm drains. The design of the storm drains depended on gravity flow for their operation. The storm drain layer was overlayed by the TIN layer using the "identity" command. Table 17, a portion of the results from the above overlay operation, shows the resulting feature attribute table. The "statistics" command was subsequently used to create a table of average slope values for each storm drain section. A relate relation was then built to access the values so that they could be used in numerical computations. The relate relation is shown in Table 15. This information can be accessed by using a statement of the form:

\&setvariable percentslope = %:edit.stormslope//mean-percent_slo%

Table 18 is the result of the two sequences of commands shown below:

```plaintext
sel poly passthru (interactively select feature within a user defined polygon)
list stormdrain2# stormslope//mean-percent_slo
```

Table 19 was the result of the following command:

```plaintext
list length pipe-size roughness shape stormslope//mean-percent_slo
```

A similar approach was also used to acquire slope information for the street pavement layer. The slope information could be accessed in a similar manner. An example is shown below:

\&setvar percentslope = %:edit.paveslope//percent_slope%

Table 20 is a portion of the result obtained when the following two sequences of
Table 17. A portion of the drainage and TIN overlay coverage, STDRAIN2TIN, feature attribute table.

<table>
<thead>
<tr>
<th>FNODEN#</th>
<th>TNODE#</th>
<th>LPOLY#</th>
<th>RPOLY#</th>
<th>LENGTH</th>
<th>STDRAIN2TIN#</th>
<th>STDRAIN2TIN-ID</th>
<th>STORMDRAIN2#</th>
<th>WARDTIN13#</th>
</tr>
</thead>
<tbody>
<tr>
<td>553</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>559</td>
<td>553</td>
<td>346</td>
<td>6877</td>
</tr>
<tr>
<td>555</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>561</td>
<td>559</td>
<td>346</td>
<td>6877</td>
</tr>
<tr>
<td>556</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>562</td>
<td>561</td>
<td>347</td>
<td>6878</td>
</tr>
</tbody>
</table>

FNODE#: 553, 555, 556
TNODE#: 558, 559, 561
LPOLY#: 7654, 6877, 6878
RPOLY#: 7654, 6877, 6878
LENGTH: 43.82771, 19.92840, 92.65028
Table 18. Average slope for selected storm drains.

<table>
<thead>
<tr>
<th>Record</th>
<th>STORMDRAIN2#</th>
<th>STORMSLOPE/MEAN-PERCENT_SLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>346</td>
<td>346</td>
<td>0.254297</td>
</tr>
<tr>
<td>347</td>
<td>347</td>
<td>0.394276</td>
</tr>
<tr>
<td>348</td>
<td>348</td>
<td>0.374375</td>
</tr>
<tr>
<td>367</td>
<td>367</td>
<td>0.374375</td>
</tr>
<tr>
<td>370</td>
<td>370</td>
<td>0.374375</td>
</tr>
<tr>
<td>388</td>
<td>388</td>
<td>0.162517</td>
</tr>
<tr>
<td>389</td>
<td>389</td>
<td>0.325034</td>
</tr>
<tr>
<td>390</td>
<td>390</td>
<td>0.325034</td>
</tr>
<tr>
<td>391</td>
<td>391</td>
<td>0.000000</td>
</tr>
<tr>
<td>392</td>
<td>392</td>
<td>0.325034</td>
</tr>
<tr>
<td>393</td>
<td>393</td>
<td>0.337086</td>
</tr>
<tr>
<td>394</td>
<td>394</td>
<td>0.337086</td>
</tr>
<tr>
<td>395</td>
<td>395</td>
<td>0.000000</td>
</tr>
<tr>
<td>396</td>
<td>396</td>
<td>0.000000</td>
</tr>
<tr>
<td>397</td>
<td>397</td>
<td>0.000000</td>
</tr>
<tr>
<td>2296</td>
<td>2296</td>
<td>0.374375</td>
</tr>
</tbody>
</table>
Table 19. Length, pipe-size, roughness coefficient, shape, average percent slope for selected storm drains.

<table>
<thead>
<tr>
<th>LENGTH</th>
<th>PIPE-SIZE</th>
<th>ROUGHNESS</th>
<th>SHAPE</th>
<th>STORMSLOPE//MEAN-PERCENT_S</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>12.000</td>
<td>0.015</td>
<td>CIRC</td>
<td>342.91079</td>
</tr>
<tr>
<td>16</td>
<td>12.000</td>
<td>0.015</td>
<td>CIRC</td>
<td>38.01400</td>
</tr>
<tr>
<td>17</td>
<td>12.000</td>
<td>0.015</td>
<td>CIRC</td>
<td>58.68092</td>
</tr>
<tr>
<td>23</td>
<td>15.000</td>
<td>0.015</td>
<td>CIRC</td>
<td>28.70196</td>
</tr>
<tr>
<td>24</td>
<td>15.000</td>
<td>0.015</td>
<td>CIRC</td>
<td>33.73692</td>
</tr>
</tbody>
</table>
Table 20. Surface characteristics and slope for selected street pavements.

<table>
<thead>
<tr>
<th>Record</th>
<th>PAVEMENT#</th>
<th>PAVESURF / SURFACE</th>
<th>PAVESLOPE / PERCENT_SLOPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>855</td>
<td>132</td>
<td>IMP</td>
<td>0.509</td>
</tr>
<tr>
<td>856</td>
<td>132</td>
<td>IMP</td>
<td>0.414</td>
</tr>
<tr>
<td>857</td>
<td>132</td>
<td>IMP</td>
<td>0.374</td>
</tr>
<tr>
<td>884</td>
<td>52</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>885</td>
<td>52</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>886</td>
<td>52</td>
<td>IMP</td>
<td>0.414</td>
</tr>
<tr>
<td>887</td>
<td>52</td>
<td>IMP</td>
<td>0.374</td>
</tr>
<tr>
<td>898</td>
<td>52</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>899</td>
<td>52</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>903</td>
<td>132</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>915</td>
<td>132</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>930</td>
<td>132</td>
<td>IMP</td>
<td>0.312</td>
</tr>
<tr>
<td>932</td>
<td>52</td>
<td>IMP</td>
<td>0.312</td>
</tr>
<tr>
<td>959</td>
<td>52</td>
<td>IMP</td>
<td>0.325</td>
</tr>
<tr>
<td>960</td>
<td>52</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>969</td>
<td>132</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>972</td>
<td>51</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>992</td>
<td>132</td>
<td>IMP</td>
<td>0.325</td>
</tr>
<tr>
<td>1000</td>
<td>132</td>
<td>IMP</td>
<td>0.325</td>
</tr>
<tr>
<td>1005</td>
<td>51</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>1010</td>
<td>132</td>
<td>IMP</td>
<td>0.000</td>
</tr>
<tr>
<td>1011</td>
<td>132</td>
<td>IMP</td>
<td>0.322</td>
</tr>
</tbody>
</table>
Several programs were written using the ARC Macro Language (AML) in order to extract and use information from the spatial database that was created. These programs used a combination of statements similar to those previously given as examples. These programs were written mainly to access the feature attribute values in the attribute tables. However, some programs were written to extract the coordinates values that defined the locations of features. One such situation was the extraction of the coordinate values for each vertex of the arcs that defined the boundaries of polygon features. By determining the maximum and minimum coordinate values in the north-south and east-west directions, the maximum length in these two directions was calculated. These two directions were chosen because they represented the predominant direction of slope for features in this watershed. These maximum lengths were subsequently used together with the coordinate values of the locations of inlets to calculate the maximum flow length to the nearest inlet. The maximum and minimum coordinate values were also used to make the decision on which set of features would contribute flow to a particular inlet. It was assumed that the inlet carried all the flow that reached it, and that there was no overflow towards the next downstream inlet. Examples of the AML programs are included in Appendix C.
Hydraulic Routing

The basic equation that describes one-dimensional unsteady free surface flow is the continuity equation:

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t)
\]  

(1)

where

- \( t = \) time, s;
- \( x = \) distance along the flow path, ft;
- \( A = \) cross-sectional flow area, ft\(^2\);
- \( Q = \) discharge, cfs;
- \( q(x,t) = \) lateral inflow, cfs/ft;

The kinematic wave assumption for the momentum equation implies that a unique relationship exists between depth and discharge in which the discharge, \( Q \), is a function of cross-sectional area, \( A \), only. This relationship can be expressed as

\[
Q = \alpha(x,t)A^m
\]  

(2)
where \( m \) is the area-discharge exponent, and \( \alpha \) is the kinematic wave friction parameter. The kinematic wave parameters, \( \alpha \) and \( m \), for overland surfaces, channels and storm drains are described by their slope, length, cross-sectional dimension, shape and roughness coefficient. The kinematic wave friction parameter, sometimes called the conveyance factor, and the area-discharge exponent of equation (2) are determined using either the Manning’s or Chezy’s uniform flow resistance laws. The Manning’s flow resistance law was used in this study to determined the kinematic wave parameters.

Kinematic Wave Modelling of Overland Flow

The kinematic wave equations for unsteady free surface overland flow can be written in one-dimensional form as (Singh, 1992):

\[
\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + h \frac{\partial u}{\partial x} = q(x,t) \tag{3}
\]

\[
Q = \alpha(x,t) h^m \tag{4}
\]
where

\( h = \) flow depth, ft;

\( t = \) time, s;

\( u = \) local average velocity, ft/s;

\( Q = \) discharge per unit width, cfs/ft;

\( x = \) distance along the flow path, ft;

\( q = \) lateral inflow or effective rainfall, ft/s;

\( \alpha \) and \( m \) are kinematic wave friction parameter and exponent respectively.

Equations (3) and (4) could be condensed into one equation by the substitution of equation (4) into equation (3) to yield,

\[
\frac{\partial h}{\partial t} + h^m \frac{\partial}{\partial x} \alpha(x,t) + \alpha(x,t)m h^{m-1} \frac{\partial h}{\partial x} = q(x,t)
\]  

Equation (5) holds in the domain \( S = \{0 < x < L, \ t > 0\} \), where \( L \) is the length of overland flow plane. When the parameter \( \alpha \) is a function of space only, equation (5) takes the form:

\[
\frac{\partial h}{\partial t} + h^m \frac{\partial}{\partial x} \alpha(x) + \alpha(x)m h^{m-1} \frac{\partial h}{\partial x} = q(x,t)
\]  

(6)
When the parameter $\alpha$ is constant, equation (6) becomes

$$\frac{\partial h}{\partial t} + \alpha m h^{m-1} \frac{\partial h}{\partial x} = q(x,t)$$

(7)

The assumption of constant $\alpha$ can be supported by the utilization of hydrologic units having a constant slope and roughness coefficient. In this study, a constant slope and roughness coefficient were assumed for each unique combination of surface and soil units that were represented as individual polygons.

Kinematic Wave Modelling of Channel Flow

The kinematic wave equations for unsteady free surface channel flow are equation (1) and equation (2) respectively. Assuming that $\alpha$ is constant and independent of time, the substitution of equation (2) into equation (1) yields

$$\frac{\partial A}{\partial t} + \alpha m A^{m-1} \frac{\partial A}{\partial x} = q(x,t)$$

(8)

Solution for Kinematic Wave Equations

The kinematic wave equations can be solved using numerical analysis techniques. A numerical analysis scheme that can be applied is the explicit finite difference approximations to the partial differential equations. As the form of the kinematic wave equations for overland flow and channel flow are similar, so is their
corresponding finite difference approximations. Following the finite difference numerical technique employed in the HEC-1 Flood Hydrograph Package (Hydrologic Engineering Center, 1990; Bedient and Huber, 1992), the finite difference approximations are made for various partial derivatives over a grid space in x and t. The computation proceeds along the x-dimensions downstream for each time step $\Delta T$ until all the flows and depths are calculated for the entire length of the overland flow surface or channel. The flows and depths are calculated from known values at previous points in x and t. The time is incremented by $\Delta T$, and the procedure is repeated for the entire length. This process is continued for the entire period of simulation. The finite difference approximation for equation (8) using the backward difference approximation can be expressed as:

$$
\frac{A_{(i,j)} - A_{(i,j-1)}}{\Delta T} + \alpha m \left[ \frac{A_{(i,j-1)} + A_{(i-1,j-1)}}{2} \right]_{m-1} + \frac{A_{(i,j-1)} - A_{(i-1,j-1)}}{\Delta x} = \frac{q_{(i,j)} + q_{(i,j-1)}}{2}
$$

(9)

therefore,

$$
A_{(i,j)} = \frac{q_{(i,j)} + q_{(i,j-1)}}{2} \Delta T + A_{(i,j-1)} - \alpha m \left[ \frac{\Delta T}{\Delta x} \right]_{m-1} \left[ \frac{A_{(i,j-1)} + A_{(i-1,j-1)}}{2} \right]_{m-1} [A_{(i,j-1)} - A_{(i-1,j-1)}]
$$

(10)

Equation (10) can be solved for $A_{(i,j)}$ and then $Q_{(i,j)}$ from equation (2).
The above series of equations that expressed finite difference approximations to the kinematic wave equations are referred to as the standard form. These equations are used if the numerical stability factor (which is based on the ratio of the wave celerity to the grid celerity), $\theta$, is less than unity (Bedient and Huber, 1992; Hydrologic Engineering Center, 1990; Smith and Alley, 1982), where $\theta$ is defined by the following equation:

\[
\theta = \frac{\alpha}{q_{(i,j)} + q_{(i,j-1)}} \frac{\Delta T + A_{(i-1,j-1)} - A_{(i-1,j-1)}^m}{2 \Delta X} \left[ \frac{q_{(i,j)} + q_{(i,j-1)}}{2} \right] \]

when $\frac{q_{(i,j)} + q_{(i,j-1)}}{2}$ greater than zero,

\[
\theta = \frac{\alpha m A_{(i-1,j-1)} m}{\Delta X} \frac{\Delta T}{\Delta x} \]

when $\frac{q_{(i,j)} + q_{(i,j-1)}}{2}$ equal zero.

If $\theta$ is greater than unity, the conservation form of the finite difference equation is used and can be expressed as:
\[
\frac{Q_{i,j} - Q_{i-1,j}}{\Delta x} + \frac{A_{i-1,j} - A_{i-1,j-1}}{\Delta T} = \frac{q_{i,j} + q_{i,j-1}}{2}
\]  

(13)

therefore,

\[
Q_{i,j} = Q_{i-1,j} + \frac{q_{i,j} + q_{i,j-1}}{2} \times \Delta x - \frac{\Delta x}{\Delta T} \times [A_{i-1,j} - A_{i-1,j-1}]
\]  

(14)

Equation (14) can be solved for \(Q_{i,j}\), then \(A_{i,j}\) is found from

\[
A_{i,j} = \left( \frac{Q_{i,j}}{\alpha} \right)^{\frac{1}{m}}
\]  

(15)

As pointed out by Hydrologic Engineering Center (1990), the accuracy and stability of the finite difference scheme is dependent on the kinematic wave speed, which is a function of the flow depth that varies as the hydrograph is routed through the drainage area.

**Hydrologic Modelling**

Urban drainage systems usually have storm water inlets to direct surface water flow into the storm sewer system. The modelling of runoff in urban areas requires the determination of inlet hydrographs for the surface areas. These inlet hydrographs, combined where necessary, are routed through the storm sewer network to produce the outflow hydrographs at the points of interest or the outlet of the drainage basin.
However, the variability of the characteristics that can be found in urban areas such as slope, land cover and topography make modelling of runoff a difficult task. This is further complicated by the fact that to adequately model the runoff response a very short time interval must be used, as small changes in rainfall intensity can be expected to produce a rapid change in the runoff hydrograph. For instance, it was shown that a 1 minute unit hydrograph can predict reasonably well the runoff from a small drainage area with varying physical characteristics (Viessman, 1966; Viessman, 1968; Miller and Viessman, 1972). Bedient and Huber (1992) suggest that rainfall data should be in increments at least 5 minutes or shorter to adequately predict the runoff hydrograph. A hypothetical rainfall at 5 minutes interval was used for this study.

The quantity of flow entering the storm sewer system is controlled by the inlets and the size of the storm sewers. The capacity and spacing of inlets determine how the flow is divided between the underground sewers and street gutters. The actual amount of surface runoff entering an inlet depends upon the design of the inlets and characteristics of the surrounding area. Inlets also tend to impose a backwater effect on the gutter flow. However, this situation will not be considered in this study. Additionally, even though the inlets in this study consist of both the curb type and grate type, they will be considered as one standard representative size and design. It was assumed that the representative inlet could convey all the flow that arrived at the inlet. It was also assumed that the size of the storm sewers was adequate to convey all the water that entered the system without backwater effect or pressurize flow.
Effective Rainfall

The duration of rainfalls is finite, with their intensities varying both spatially and temporally. In the urban environment, two types of rainfall information are of interest (Chow and Yen, 1976): (1) The duration and maximum intensity for rainfalls that have long return periods, which are used for design and safety considerations; (2) High frequency rainfalls with return periods less than a year, which are used for operation and pollution control purposes.

Infiltration, the process of water flowing through the ground surface, is a major factor affecting surface runoff. Other factors that affect surface runoff include interception, evaporation, transpiration and depression storage. These losses are generally considered as total combined losses to total precipitation and are referred to as total abstractions or, simply, abstractions.

The major factors influencing the rate of infiltration are soil types and moisture content (Viessman et al., 1989). The soil type characterizes the size and number of passages through which the water must flow, while the moisture content sets the capillary potential and relative conductivity. Capillary potential is the hydraulic head due to capillary forces, and relative conductivity is the capillary conductivity for a specified moisture content divided by the saturated conductivity (Viessman et al., 1989).

Three general cases of infiltration can be associated with rainfall (Mien and Larson, 1973). In the first case, the rainfall rate is less than the saturated conductivity of the soil. Under this condition runoff never occurs, as all the rainfall infiltrates into
the surface of the soil. In the second case, the rainfall rate is greater than the saturated conductivity but is less than the infiltration capacity. For this condition, all rainfall infiltrates into the soil and the soil moisture level near the soil surface increases. This increase continues until surface saturation occurs, that is, the infiltration capacity is reached. In the final case, the rainfall rate is greater than the infiltration capacity. For this condition, the infiltration rate is at the infiltration capacity and runoff is being generated. After surface saturation occurs and the rainfall ends or becomes less than the infiltration capacity, the practice in hydrologic modelling is to allow any ponded water to infiltrate, and the infiltrated water is added to the cumulative infiltration volume.

Figure 3 indicates the kind of soils that exist in the upper portion of the Ward Creek watershed. Soils are classified into hydrologic soil groups based on their minimum infiltration rate (U.S. Department of Agriculture, 1986). Soils in the study area consist of soil series that are classified into hydrologic soil groups C and D, as determined from SCS Technical Release 55 (U.S. Department of Agriculture, 1986). Soils in hydrologic soil group C are soils having slow infiltration rates if thoroughly wetted, therefore having a slow rate of water transmission. Soils in hydrologic soil group D are soils that have a very slow infiltration rate if thoroughly wetted; therefore, they have a very slow rate of water transmission. The information relating the hydrologic soil group to the curve number as a function of soil cover, land use type and antecedent moisture conditions was obtained from the SCS publication Technical Release 55 (U.S Department of Agriculture, 1986).
For this study, rainfall excess was determined by a modified Soil Conservation Service (SCS) curve number method (U. S. Department of Agriculture, 1986). The modification took into consideration the current state of the soil moisture storage. This was achieved through an accounting procedure that required knowledge of the thickness of the soil horizons, soil water capacity and hydraulic conductivity of the soil under consideration (Figure 9). Even though the SCS curve number method was not designed to estimate infiltration directly, by taking into account the effects of land use and treatment, it indirectly considered infiltration. As the curve number tends to vary with soil moisture, Williams and LaSeur (1976) used a soil moisture accounting procedure for its estimation which was found to increase the accuracy of runoff prediction. For this study, the modification of the SCS curve number method was based on the premise that the moisture holding and moisture transmitting characteristics of the soil and the rainfall intensities were the most important factors governing the runoff volumes from small watersheds such as those considered in an urban environment. In this respect the characteristics of the top soil layer were critical, as it was the only soil layer that may have significantly affected the dynamic infiltration process (Fok and Chiang, 1984; Singh and Yu, 1990).

In determining the rainfall excess, the infiltrated water that enters the surface layer of the soil profile is assumed to increase the soil water in storage, which is continuously being reduced by percolation (Figure 9). Before saturation occurs, percolation is assumed to be at half the rate of the saturated hydraulic conductivity, and all the water infiltrates the soil if the rainfall intensity is less than the infiltration
Figure 9. Block diagram of a soil profile showing components of the model for calculating the effective rainfall.
rate. If rainfall intensity is greater than the infiltration rate, the volume of rainfall is distributed between surface runoff and infiltration based on the amount of water that can be infiltrated during the specific time interval. When the available storage is exceeded, the soil water then percolates out of storage at the rate of the saturated hydraulic conductivity of the soil. When the available water capacity is filled, all additional precipitation less percolation is assumed to contribute directly to the runoff volume. As noted by Ligon et al. (1965), runoff may occur during periods of intense rainfall, even though the moisture content of the soil is below field capacity. However, as suggested by Haan (1972), this problem can be overcome through the utilization of hourly precipitation data instead of daily precipitation data. A number of techniques are available that can be used to transform daily rainfall data into hourly or fractions of a hour intervals rainfall data (Haan, 1972). A mechanism was established to determine whether the amount of water coming out of storage exceeded that which came into storage by accounting for the water that entered or left storage at every time step. If such a situation existed, the percolation would revert back to the rate prior to precipitation until such time that the field capacity was again exceeded.

The form of the SCS curve number method used to calculate the rainfall excess is the form described by Smith and Williams (1980):

\[
ACCRE = \frac{(CUMPRECIP1 - 0.2S)^2}{CUMPRECIP1 + 0.8S}
\]
where ACCRE is the cumulative rainfall excess in inches, CUMPRECIP1 is cumulative precipitation in inches, S is a retention parameter in inches. The retention parameter, S, is related to soil water content with the following equation:

$$S = SMX \left( \frac{UL - SM1}{UL} \right)$$  \hspace{1cm} (17)$$

where UL is the upper limit of soil water storage in the soil layer in inches, SM1 is the soil water content in the layer in inches, and SMX is the maximum value of S. The maximum value of S is estimated with the antecedent moisture condition curve number (CN) using the following SCS equation:

$$SMX = \frac{1000}{CN} - 10$$  \hspace{1cm} (18)$$

CN is the SCS curve number, an index to represent the combined hydrologic effects of soil, land use, agriculture land treatment class, land management practices, hydrologic condition and antecedent soil moisture (McCuen, 1982). As designated by the SCS, the curve number CN1 is for antecedent conditions where the soils are dry but not to wilting point and when satisfactory cultivation has taken place. The curve number CNII is for average antecedent conditions that preceded the occurrence of the maximum annual flood on numerous watersheds. The curve number CNIII is for
antecedent conditions where heavy rainfall or light rainfall and low temperatures have occurred during the 5 days previous to the given storm, and the soil is nearly saturated. Depending on the antecedent conditions, the appropriate curve number could be selected for use in the model, and the changing soil moisture conditions were accounted for by keeping track of the changing amount of water in the soil water storage. When a CN\textsubscript{i} is selected for use in the model, the value of CN\textsubscript{i} is computed from values of CN\textsubscript{n} using the following polynomial defined by Smith and Williams (1980):

\[ CN_I = -16.91 + 1.348(CN_n) - 0.01379(CN_n)^2 + 0.0001177(CN_n)^3 \quad (19) \]

The model does not currently support the antecedent moisture conditions that require curve number CN\textsubscript{iii}. At the end of each period, the soil moisture (SM1) is increased by the amount of infiltration (the difference between the cumulative precipitation and cumulative rainfall excess) less the amount of percolation. Since the method gives cumulative rainfall, the incremental excess for a time period is calculated as the difference between the cumulative excess at the end of the current period and the cumulative excess at the end of the previous period. Rainfall excesses are determined for each polygon that represents a pervious or impervious area defined as a hydrologic response unit.
Modelling Strategy

The model components described in the previous paragraphs were employed for the modelling of the Ward Creek watershed using the spatial database created with the GIS. The model inputs are attributes that described the physical characteristics of the watershed, which are stored in the spatial database (Figure 10).

The discharge hydrographs were determined using a model based on the kinematic wave equations. For the determination of overland flow, the model required as input the effective rainfall, maximum flow length and equivalent width, roughness coefficient and slope. For routing the hydrographs, the physical characteristics of the routing element need to be specified, such as the length, slope, roughness coefficient, width or diameter, side slope and shape. The routing element can either be a gutter, a storm drain or a stream channel.

The effective rainfall was determined for each hydrologic response area using the modified SCS method described. The method required that the curve number, antecedent moisture condition, saturated hydraulic conductivity and soil moisture storage capacity be specified for each hydrologic response area. These were all obtained from the spatial database of the watershed, except for the antecedent moisture condition, the total simulation time, the simulation time increment and the number of overland and channel intervals for the finite difference scheme that were specified interactively.

The discharge hydrographs were determined for each hydrologic response area and routed to the nearest inlet, where they were combined to form the total overland
Figure 10. Schematic diagram for modeling.
hydrograph at the inlet location. The inlet was assumed to have the capacity to carry all the overland flow that arrived at that location. In the storm drain, the total overland hydrograph was combined with the upstream flow and routed to the next inlet location. The process was repeated at every inlet until the outlet location was reached.

Polygons representing unique hydrologic soil group and surface characteristics were treated as hydrologic response areas. Values for curve number, roughness coefficient and slope were assigned using the GIS technique previously described. The locational information that defined each polygon provided the data needed to determine the overland flow length for each hydrologic response area and to determine which of these areas contributed to the flow at a particular location, such as an inlet in an urban area.

The boundaries of polygons are defined by a series of arcs that are actually a series of points with x- and y- coordinates values. In GIS, these x- and y- coordinates are generally not readily available to the user but are used by the system for feature manipulations. However, the coordinate values can be accessed through high level programming within the GIS environment.

Since the major focus of this study was to include the spatial heterogeneity of the watershed in the modelling process, a series of programs were written within the GIS environment to extract and use these x- and y- coordinate values. The predominant slope directions in this study area were north and south. These directions were used as the aspects of the polygons that represented the hydrologic response
areas. A series of programs were written to extract the maximum and minimum coordinate values for every polygon, which are defined by arcs in coverages of the study area. The maximum and minimum coordinate values for every polygons were used to calculate the length of the polygons in both directions. The polygons were subsequently conceptualized as rectangles, and the area of each polygon was divided by the lengths in both x- and y- directions to give an equivalent width for every polygon. Examples of these programs are included in Appendix C.

The polygons that represent the hydrologic response areas are defined by the arcs in the coverage of the GIS. The endpoints (nodes) of the arcs and the change of directions along the arcs are defined by vertices. The maximum and minimum x-coordinate values for every polygon were determined by comparing the x-coordinate values of every vertex for each arc which defined each polygon. A similar comparison was made to determine the maximum and minimum y-coordinates for each polygon in the coverage. The maximum lengths of the polygons in x- and y-directions were calculated as the difference between the maximum and minimum coordinate values. In this study, the maximum lengths of the polygons were determined only in the x- and y-directions; however, a similar approach using the coordinates could be followed to calculate lengths in any direction of the polygon.

The maximum and minimum coordinates values in both directions were stored in the feature attribute table of the arc and polygon coverages that represent the characteristics of the watershed. Similar algorithms were written to extract the x- and y-coordinate values for location of the inlets and junctions of the storm drain
network. The inlets and junctions were represented as nodes in the storm drain network coverage. The x- and y- coordinates values were stored in the feature attribute table of the arc coverage used to represent the storm drain network.

The maximum and minimum coordinate values extracted were used to guide the modelling of runoff through the storm drainage network. Figure 11 is a typical example of the street block that could be found in the Ward Creek watershed. Figure 12 is the routing schematic for the street block shown in Figure 11. Figure 12 shows how the drainage network can be used to guide the modelling of runoff from the elements of the block to the outlet. A series of programs were 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 by the computer model to determine the discharge hydrographs at the inlets and outlet.

In order to run the model, the inlet receiving the flow downstream and the nearest inlet upstream had to be identified and their x- and y-coordinate values extracted. The identification of the inlets also allowed the physical characteristics of the storm drain connecting the inlets to be obtained from the database. Hydrologic response areas, represented by polygons, the boundaries of which were defined by coordinate values between the extracted inlets coordinate values, were considered to contribute to the flow arriving at the receiving inlet and their attributes were acquired from the database. Based on the coordinate values of the receiving inlet and the boundaries of the polygons, the overland flow and gutter lengths were calculated for
Figure 11. A typical street block for the Ward Creek watershed showing the elements of the block.
Figure 12. Drainage network and routing schematic for street block shown in Figure 11.
each polygon. The maximum flow length was calculated as the maximum length of
the individual polygon in the direction of flow plus the additional overland distance
the water from the polygon had 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 inlet downstream.

Figures 11 and 12 can be used to illustrate the approach described above.
Inlets no. 5 and no. 6 are identified as the downstream and upstream inlets,
respectively. The x- and y- coordinate values for the identified inlets are extracted
from the spatial database. The inlets coordinate values are also the coordinate values
for the endpoints of the connecting storm drain, and this allows the storm drain to be
identified. The identification of the connecting storm drain will allow the extraction
of its physical characteristics from the database such as the length, slope, roughness
coefficient, diameter or width, and shape. The coordinate values for inlets no. 5 and
no. 6 can be used to select polygons whose coordinate values are between those for
the inlets, such as polygons no. 7 and no. 8. After the polygons are selected, the
attributes for each polygons are extracted from the database, such as the polygon
number, surface characteristics, slope, roughness coefficient, curve number, soil
saturated hydraulic conductivity, soil water storage capacity and equivalent width.
The maximum flow length of every polygon is calculated by determining if the
polygon maximum y-coordinate value is less than the inlet no. 5 y-coordinate value.
If the polygon maximum y-coordinate value is less than the inlet no. 5 y-coordinate
value, the maximum flow length of the polygon is equal to inlet no. 5 y-coordinate value minus the polygon maximum y-coordinate value plus the polygon maximum y-length. Otherwise the maximum flow length is equal to the polygon maximum y-length. The y-length is defined as the maximum length of the polygon in the y-direction. The difference between the polygon minimum x-coordinate and the x-coordinate of the inlet downstream (inlet no. 5) could be used as the length of the gutter.

The resulting information for the polygons and storm drains are written into separate output files. Examples of these results are given in appendices A and B. The routing programs read the output files and use the inlet numbers for the storm drains to guide the modelling to the outlet point. This approach can be used throughout the coverage for every street block in the watershed.
RESULTS AND DISCUSSION

The modelling strategy outlined above was demonstrated for two portions in the upper Ward Creek watershed designated as AREA A (Figure 13) and AREA B (Figure 14), respectively. AREA A represents a street block subdivided into lots, which were further subdivided into polygons that represent pervious and impervious areas (Figure 15). AREA B represents an area that consists of two street blocks which were subdivided based on the imperviousness of both blocks, with each polygon either representing a pervious or an impervious area (Figure 16). The drainage network for these areas consists of gutters, ditches, inlets and storm drains (Figures 17 and 18). The drainage network guided the extraction of the needed information from the database and the routing of surface discharge to the outlet. Appendices A and B contain typical examples of the data that were extracted from the spatial database.

The hypothetical rainfall event shown in Figure 19 was used as the rainfall input to the hydraulic model. The event had two peak rainfall intensities that occurred at 135 and 180 minutes after the rainfall began. The modified SCS model previously described was used to determine the effective rainfall for each polygon as the result of the given rainfall event. For example, Figure 20 represents the effective rainfall for polygon 11 of AREA A, as determined by the modified SCS model. Polygon 11 represents a pervious area with a curve number of 74, a saturated hydraulic
Figure 13. Polygon numbers for AREA A in the upper Ward Creek watershed.
Figure 14. Polygon numbers for AREA B in the upper Ward Creek watershed.
Figure 15. Pervious and impervious areas for AREA A.
Figure 16. Pervious and impervious areas for AREA B.
Figure 17. Drainage network for AREA A.
Figure 18. Drainage network for AREA B.
Figure 19. A hypothetical rainfall event.
Figure 20. Effective rainfall for polygon no. 11 of AREA A.
conductivity of 0.100 in/hr, a soil moisture capacity of 2.25 inches, and an antecedent moisture conditions of II based SCS designation.

Effects on Discharge Due to Scalar Changes

The hydrograph shown in Figure 21 represents the discharge for AREA A as a result of the hypothetical rainfall event (Figure 19). It represents the discharge determined at inlet number 18, which was considered to be the outlet of AREA A (Figure 17). The discharge hydrograph for AREA A was a double peak hydrograph that reflected the peaks in the rainfall event. The first peak, which was the highest of the two peaks, occurred at a time of 140.0 minutes after the rainfall began with a discharge of 4.635 cfs. The discharge for the second peak was 4.363 cfs, which occurred at 185 minutes after the rainfall commenced. Both of these peaks occurred 5 minutes after the peaks in the rainfall event, which indicated that there was some delay in the overall response to the rainfall event as a result of storage within the block.

For AREA B, the discharge was determined at inlet numbers 24 and 34 (Figure 18). Inlet number 24 corresponds to the outlet location for AREA A, and inlet number 34 was the outlet for AREA B. The peak discharge at inlet number 24 was 4.357 cfs (Figure 22), which was 6.0% lower than the peak discharge of 4.635 cfs obtained for AREA A (Figure 21). The peak discharge in both cases occurred 140 minutes after the beginning of the rainfall event. The discharge for the second peak at inlet number 24 in AREA B was 3.990 cfs at 185 minutes, which was 8.5% lower
Figure 21. Discharge hydrograph at outlet of AREA A for existing conditions.
Figure 22. Discharge hydrograph for AREA B at the same location as the outlet of AREA A for existing conditions.
than the second peak discharge of 4.363 cfs at the same time for AREA A (Figure 21). The difference in the peak discharges for AREA A and AREA B suggests that the size of the hydrologic response areas as represented by the polygons had some influence on the calculated discharges. The amount of influence that the size of the hydrologic response areas had and the determination of an optimum size should be subject to further investigation. The hydrograph in Figure 23 represents the discharge at the outlet of AREA B. The peak discharge at the outlet was 10.240 cfs at 145 minutes after the rainfall began. The discharge for the second peak was 9.355 cfs at 190 minutes.

Effects on Discharge Due to Spatial Changes

In order to examine the effects changes in the watershed characteristics had on the discharge hydrograph of AREA A, a number of simulations were made with changes to the surface characteristics while retaining the same rainfall event. The changes were made to existing lots that were considered pervious at various locations in the block. Impervious conditions were simulated by changing the existing curve number to 98 and the existing roughness coefficient to 0.010. The lots were changed sequentially to impervious conditions, and the discharge hydrographs at the nearest inlet and the outlet were determined. Figures 24 and 25 are the discharge hydrographs at the outlet (inlet no. 18, Fig. 17) and Figure 26 through Figure 28 are the discharge hydrographs at the nearest inlet (inlet no. 8, Fig. 17). Figure 26 represents the discharge at the nearest inlet (inlet no. 8) under existing conditions.
Figure 23. Discharge hydrograph at outlet of AREA B for existing conditions.
Figure 24. Discharge hydrograph at outlet of AREA A with polygon no. 11 impervious.
Figure 25. Discharge hydrograph at outlet of AREA A with polygon no. 9, 10, 11, and 12 impervious.
Figure 26. Discharge hydrograph at inlet no. 8 of AREA A for existing conditions.
Figure 27. Discharge hydrograph at inlet no. 8 of AREA A with polygon no. 11 impervious.
Figure 28. Discharge hydrograph at inlet no. 8 of AREA A with polygon no. 9, 10, 11, and 12 impervious.
The effects of the increased imperviousness on the peak discharges at the nearest inlet and outlet are tabulated in Table 21.

The results tabulated in Table 21 show that when compared to the peak discharge for the existing conditions, there was no significant change in the peak discharge at the outlet. However, there were notable increases in the peak discharge at the nearest inlet. For example, when polygon 11 was made impervious, the peak discharge at 135 minutes increased by 16.1% at the nearest inlet (Figure 27) and only increased 0.6% at the outlet at 140 minutes after rainfall onset (Figure 24). For the second peak, the discharge increased by 21.7% at the inlet at 180 minutes and 1.0% at the outlet at 185 minutes after the rainfall began. When all the lots that contributed to the flow at inlet no. 8 were made impervious, there was an increase of 45.6% at the inlet at 135 minutes (Figure 28) and 1.5% at the outlet at 140 after the rainfall commenced (Figure 25). Also, the second peak discharge increased by 63.5% at the inlet at 180 minutes and 2.9% at the outlet at 185 minutes after the rainfall began. The increase in the peak discharge at the inlet was more rapid than that observed at the outlet when similar changes were made to the polygons surface characteristics. Also, as can be seen in Figures 26 through Figure 28, the shape of the hydrograph at the inlet changed as the surfaces that contributed to the flow became impervious, resulting in more runoff volume at an earlier time. In addition, the hydrographs became more reflective of the rainfall event, in the sense that the peak at the later time increased at a faster rate than the peak at the earlier time to reflect the higher intensity of rainfall that occurred at the later time. This change in the volume under
Table 21. Summary of peak discharges at the nearest inlet and outlet of AREA A.

<table>
<thead>
<tr>
<th>Polygon(s) made impervious</th>
<th>Change peak discharge at inlet no. 8</th>
<th>Percent increase</th>
<th>Change in peak discharge at outlet</th>
<th>Percent increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing conditions</td>
<td>0.502 cfs @ 135 min (Fig. 26)</td>
<td></td>
<td>4.635 cfs @ 140 min (Fig. 20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.452 cfs @ 180 min</td>
<td></td>
<td>4.363 cfs @ 185 min</td>
<td></td>
</tr>
<tr>
<td>polygon no. 11</td>
<td>+0.081 cfs @ 135 min (Fig. 27)</td>
<td>16.1%</td>
<td>+0.027 cfs @ 140 min (Fig. 24)</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>+0.098 cfs @ 180 min</td>
<td>21.7%</td>
<td>+0.045 cfs @ 185 min</td>
<td>1.0%</td>
</tr>
<tr>
<td>polygons no. 9, 10, 11, 12</td>
<td>+0.229 cfs @ 135 min (Fig. 28)</td>
<td>45.6%</td>
<td>+0.069 cfs @ 140 min (Fig. 25)</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>+0.287 cfs @ 180 min</td>
<td>63.5%</td>
<td>+0.126 cfs @ 185 min</td>
<td>2.9%</td>
</tr>
</tbody>
</table>
the second peak of the discharge hydrograph occurred even though the volume under the second peak of the rainfall was less than the volume under the rainfall first peak. The difference in rate of increase of the peak discharge at the inlet and outlet suggests that the locations where the discharge are determined is important when effects of changes are investigated. These results also show that changes in the surface characteristics for individual polygons had effects on the discharge at the inlet, even though the effects on the outlet discharge were not significant. By monitoring the effects of the changes at the inlet it was possible to observe the contribution made by the individual polygons to the total discharge at the inlet. It would also be possible to evaluate the inlet capacity to carry the additional flow due to the changes in the surface characteristics.

To get a better understanding of the behavior of runoff for individual polygons, two polygons at different locations in AREA A were selected for detailed investigation using the same rainfall event. The first polygon selected was polygon number 11. Figure 29 is the overland discharge hydrograph for polygon number 11 before it was routed to the nearest inlet. The hydrograph indicated a peak discharge of 0.110 cfs at 135 minutes after rainfall began. When the overland discharge was routed to the nearest inlet (inlet number 8) the peak discharge reduced to 0.097 cfs, but it was at the same time of the overland peak discharge (Figure 30). The routing of the polygon discharge to the outlet resulted in the further reduction of the peak discharge to 0.081 cfs and an increase in the time to peak to 145 minutes after the beginning of the rainfall event (Figure 31). The second polygon selected for the detailed investigation
Figure 29. Overland discharge hydrograph for polygon no. 11 of AREA A.
Figure 30. Polygon no. 11 discharge hydrograph routed to the nearest inlet (inlet no. 8) of AREA A.
Figure 31. Polygon no. 11 discharge hydrograph routed to the outlet of AREA A.
was polygon number 32, which was further upstream than polygon number 11 in AREA A and further away from the outlet. The effective rainfall for polygon number 32 is shown in Figure 32. Figure 33 represents the overland discharge hydrograph, which indicated a peak discharge of 0.117 cfs at 135 minutes after the rainfall began. The second peak discharge was 0.104 cfs at 180 minutes. The peak discharge for the routed discharge hydrograph at the nearest inlet (inlet no. 10) was 0.099 cfs at 140 minutes (Figure 34) and at the outlet was 0.079 cfs at 190 minutes (Figure 35). However, the shape of the discharge hydrograph as shown in Figure 35 also shows the effects that the surface roughness coefficient had on the overland discharge hydrograph as it was routed to the outlet. These effects are clearly seen in the drastic reduction in the first peak and the increased volume under the second peak of the routed discharge hydrograph. The reduction in the peak discharge, the increase in time to peak, and the shift in volume are the result of storage that occur within the storm drains as it was routed to the outlet.

The surface characteristics of polygon number 11 were changed from that of a pervious polygon (curve number = 74, roughness coefficient = 0.100) to that of an impervious polygon (curve number = 98, roughness coefficient = 0.010). Figures 36 and 37 are, respectively, the overland discharge and routed hydrographs for an impervious polygon number 11. Figure 36 indicated a peak discharge of 0.205 cfs at 180 minutes, which was a 107.1% increase in the peak discharge of 0.099 cfs at 180 minutes for polygon number 11 under the existing conditions (Figure 29). The hydrograph in Figure 36 also shows a second peak discharge of 0.186 cfs at 135
Figure 32. Effective rainfall for polygon no. 32 of AREA A.
Figure 33. Overland discharge hydrograph for polygon no. 32 of AREA A.
Figure 34. Polygon no. 32 discharge hydrograph routed to the nearest inlet (inlet no. 10) of AREA A.
Figure 35. Polygon no. 32 discharge hydrograph routed to the outlet of AREA A.
Figure 36. Overland discharge hydrograph for impervious polygon no. 11 of AREA A.
Figure 37. Discharge hydrograph for impervious polygon no. 11 of AREA A routed to nearest inlet (inlet no. 8).
minutes, a 69.1% increase in the peak discharge of 0.110 cfs at the same time for the discharge under the existing conditions. The discharge hydrograph impervious polygon number 11 was routed to the nearest inlet (inlet number 8), and the peak discharge was 0.181 cfs at 180 minutes after the beginning of the rainfall event (Figure 37). The peak discharge for the routed hydrograph was 94.6% greater than the peak discharge of 0.093 cfs at 185 minutes for the routed hydrograph under existing conditions (Figure 30). As shown in Figure 37, the second peak discharge of 0.179 cfs that occurred at 135 minutes was 84.5% greater than the peak discharge of 0.097 cfs at the same time under existing conditions.

Sensitivity of Discharge to Surface Roughness Coefficient

The sensitivity of discharge to various surface characteristics was investigated by changing the roughness coefficient for polygon number 32. The overland discharges were determined for the polygon, with the roughness coefficient ranging from 0.01 to 0.07 and an existing conditions curve number of 74. The hydrograph shown in Figure 38 represents the discharge for the polygon when the existing conditions roughness coefficient was reduced 30% to 0.07. It shows a peak discharge of 0.136 cfs at 135 minutes after the rainfall began and a second peak discharge of 0.123 cfs at 180 minutes. The observed discharge was 16.2% higher than the peak discharge of 0.117 cfs for the existing conditions (Figure 33). The second peak was also 18.3% higher than the second peak of 0.104 cfs for the existing conditions. When the existing conditions roughness coefficient was reduced by 50% to 0.05, the
Figure 38. Discharge hydrograph for polygon no. 32 of AREA A with roughness coefficient of 0.07.
peak discharge was 0.151 cfs at 135 minutes and the second peak was 0.140 cfs at 180 minutes (Figure 39). Both peak discharges were respectively 29.1% and 34.6% higher than the peak discharge at 135 minutes and second peak discharge at 180 minutes for the existing conditions. Figure 40 represents the discharge when the existing conditions roughness coefficient was reduced by 70% to 0.03. The discharge in both peaks was almost identical with 0.166 cfs at 135 minutes and 0.164 cfs at 180 minutes. These discharges were respectively 41.8% and 57.7% higher than the discharge for the two peaks at the corresponding times for the existing conditions. When the existing conditions roughness coefficient was reduced by 90% to 0.01, the peak discharge was 0.200 at 180 minutes (Figure 41) with a second peak of 0.182 cfs at an earlier time (135 minutes). Both peaks were 92.3% and 55.6% higher than the peak discharge at 180 minutes and the second peak discharge at 135 minutes after the rainfall began for the existing conditions. The occurrence of the higher peak discharge at the later time indicated that as the roughness coefficient got closer to that for impervious conditions, the discharge hydrograph became more reflective of the rainfall event. The rainfall event had two peaks, with the one at the later time of higher intensity. When the resulted hydrographs were compared to Figure 33, the discharge hydrograph for the existing conditions, a gradual increase in the peak discharge was observed. These results suggest that even if the surface was not made totally impervious, the conditions of the polygon as reflected by the roughness coefficient would have an effect on the discharge from that surface.
Figure 39. Discharge hydrograph for polygon no. 32 of AREA A with a roughness coefficient of 0.05.
Figure 40. Discharge hydrograph for polygon no. 32 of AREA A with a roughness coefficient of 0.03.
Figure 41. Discharge hydrograph for polygon no. 32 of AREA A with a roughness coefficient of 0.01.
Effects on Discharge from AREA B Due to Spatial Changes

The discharge hydrograph at the outlet of AREA B is shown in Figure 23 and to examine the effects changes in the surface characteristics would have on the discharge two polygons were selected. The first polygon (polygon number 87) was situated close to the outlet of AREA B, and the second polygon (polygon number 29) was further upstream than the first polygon. The polygons' surface characteristics were changed from pervious to impervious by changing the roughness coefficient from its existing value to 0.010 and the curve number from its existing value to 98. Figures 42 and 43 are discharge hydrographs at the outlet of AREA B as a result of these changes. Figure 42 is the discharge hydrograph as a result of changes made to polygon number 87, and it shows a peak discharge of 10.227 cfs at 145 minutes after the rainfall began which was a 0.13% decrease in the peak discharge from that for the existing conditions. It also shows a second peak discharge of 9.479 cfs at 190 minutes which was a 1.3% increase in the second peak discharge. Figure 43 is the discharge hydrograph as a result of changes made to polygon number 29, and it shows a peak discharge of 10.385 cfs at 145 minutes and a second peak of 9.547 cfs at 190 minutes. Both of these results indicate that there were respectively 1.4% and 2.0% increase in the corresponding peak discharges as a result of the surface being made impervious from the peak discharge of 10.240 cfs at 145 minutes and 9.355 cfs at 190 minutes that occurred under the existing conditions (Figure 23). The small changes in magnitude of the peak discharges suggest that at the scale of the hydrologic response areas evaluated, the effects of spatial changes within AREA B are minimal.
Figure 42. Discharge hydrograph at the outlet of AREA B with polygon no. 87 impervious.
Figure 43. Discharge hydrograph at the outlet of AREA B with polygon no. 29 impervious.
CONCLUSIONS

The results of this study demonstrate that GISs could be used to provide the information required for a realistic analysis of runoff from an urban watershed. Through the utilization of the spatial analysis capabilities of a GIS, it was possible to represent an urban watershed realistically for the modelling of runoff. The approach employed in this study demonstrated that the coordinate values that define the locations and boundaries of features in the GIS could be used for spatial analysis. The coordinate values were used to identify (1) which hydrologic response areas contributed to the flow at a particular inlet and (2) the storm drain that connected the identified inlet to the next downstream inlet. The attributes that described the characteristics of the hydrologic response areas and storm drains were subsequently extracted for later use in the hydrologic model. The coordinate values were also used to calculate the flow length for each hydrologic response area. As the current trend towards the creation of extensive and comprehensive geographic databases continues, the approach used in this study would be useful for hydrologic applications with such geographic databases. For instance, the approach described would be useful for water quality applications in an urban environment where there are multiple, spatially diverse, sources of pollution.

The peak discharges of AREA B, which was divided into hydrologic response areas based on the imperviousness of the blocks, were respectively 6.0% and 8.5% higher than the corresponding peak discharges in AREA A. AREA A was divided
into hydrologic response areas based on the imperviousness of the lots within the block. It was concluded that although the resolution of the hydrologic response areas had some influences on the calculated discharges more investigation was needed to quantify the influences and determine an optimum size for the hydrologic response areas.

The investigation on the effects changes in surface characteristics at various locations might have on the discharge showed that even though there was little or no impact on the discharge at the outlet, there was a larger impact at the nearest inlet receiving the flow from the surfaces. For instance, when all the surfaces that contributed to the flow at a particular inlet were made impervious, one of the two peaks in discharge hydrograph increased by as much as 63.5% at the nearest inlet but only 2.9% at the outlet. These results suggest that when the impact of development on discharge is being investigated, the location at which the discharge is determined is critical. The discharge should be determined at that part of the drainage network closest to the site of development. This is also true for individual lots, as the investigation showed that one of the two peaks in the discharge hydrograph increased 21.7% at the nearest inlet and only increased by 1.0% at the outlet.

The effects on discharge due to the changes in the surface roughness coefficient was also investigated. It was concluded that the discharge was very sensitive to the roughness coefficient. Any temporary conditions that change the roughness coefficient of the surface would cause a change in the discharge. When the roughness coefficient of a surface was varied between the range of 0.01 and 0.100, an increase of as much
as 92.3% was observed in the peak discharge. This increase was observed even though the surface was considered pervious and had a curve number of 74. These results therefore suggest that the condition in which the individual lots are kept has an impact on the discharge that would prevent or encourage flooding in that vicinity.

Even though this study was able to demonstrate how geographic information systems could be used to evaluate what effects various changes would have on discharge, it has a drawback in that it lacks actual field calibration. Due to the absence of observed discharges at various locations in the watershed, a comparison with the calculated discharges was not possible. However, the lack of calibration is not so severe due to the fact that the model is physically based and that the parameters, curve number and roughness coefficient, have shown to give a good description of the watershed conditions. Also, the lack of sufficient rainfall gages in the watershed to support the detailed data utilized in this study accounts for the use of a hypothetical rainfall event. It is recommended that the study be extended to include actual rainfall data and observed discharges so that a more realistic evaluation of the approach presented can be made. It is also recommended that the location at which the discharge is determined when considering the impact of changes in watershed conditions be the existing drainage network location closest to the site of the changes instead of the outlet of the drainage area or watershed.
REFERENCES


APPENDICES
Appendix A: Typical Spatial Database Output - Surface Characteristics

In appendix A, data that contributed to the flow at a particular inlet were separated from the data for the previous inlet by a code (-99999). The first row immediately after the code was the inlet number and its x- and y-coordinates. The second row after the code and every other row until the next code contains information from the surface polygons that contributed to the flow at the inlets. The information included in the second row in order are the polygon number, pervious (PER) or impervious (IMP) surface, flow length, slope roughness coefficient, curve number, saturated hydraulic conductivity, soil water storage and equivalent width. The third row and every other row after the codes, contain information for the gutter or ditch that conveyed the flow from the surface polygon in the previous row to the nearest inlet. The information included in the third are the gutter or ditch length, slope, roughness coefficient, width or diameter, side slope and shape.
Appendix B: Typical Spatial Database Output - Channel Characteristics

In appendix B, the information for the storm drain connecting two successive inlets are in each row. The information in order are the previous inlet number, inlet number, length of storm drain, roughness coefficient, width or diameter, side slope and shape. The previous inlet number was used to identify the inlet that received the runoff from the various surfaces.
Appendix C: Typical ARC/INFO Arc Macro Language Programs. Programs were used to access and manipulate spatial database.
/* Program XPCoord.aml to extract x-coordinate from each vertex of the polygon */
/* The program take the coverage name as a argument */
&args cover
/* arcedit */
/* display 9999 */
edit %cover%
edit arc
select all
&sv an := 1 /* an represent the arc number */
do &while %an% le [show number select]
 &sv vn := 1 /* vn represent the vertex number */
do &while %vn% le [show arc %an% npnca]
 &sv xcoord%vn% := [extract 1 [show arc %an% vertex %vn%]]
/* find the maximum and minimum x-coordinate */
if %vn% ge 2 then
do
 &sv maxxcoord := %maxxcoord%
 &sv minxcoord := %minxcoord%
 &sv maxxcoord := [max %maxxcoord% [value xcoord%vn%]]
 &sv minxcoord := [min %minxcoord% [value xcoord%vn%]]
end
else
do
 &sv maxxcoord := %xcoordl%
 &sv minxcoord := %xcoordl%
end
 &sv vn := %vn% + 1
end
select %cover% = %an%
calculate xmax = %maxxcoord%
calculate xmin = %minxcoord%
&sv an := %an% + 1
select all
&end
save
&return
/* Program YFCOORD2.vml to extract coordinate from each vertex of the polygon */
/* The program take the coverage name as a argument */
$args cover
/* arcedit */
/* display 9999 3 */
edit %cover%
editf arc
select all
&sv an := 1 /* an represent the arc number */
do &while %an% le [show number select]
&sv vn := 1 /* vn represent the vertex number */
do &while %vn% le [show arc %an% npnts]
&sv ycoord%vn% := [extract 2 [show arc %an% vertex %vn%]]
/* find the maximum and minimum y-coordinate */
&sv maxycoord := %ycoordl%
&sv minycoord := %ycoordl%
&sv maxycoord := [max %maxycoord% [value ycoord%vn%]]
&sv minycoord := [min %minycoord% [value ycoord%vn%]]
&end
&else
&do
&sv maxycoord := %ycoordl%
&sv minycoord := %ycoordl%
&end
&sv vn := %vn% + 1
&end
select %cover% = %an%
calculate ymax = %maxycoord%
calculate ymin = %minycoord%
&sv an := %an% + 1
select all
&end
save
&return
/*Program XPOLYMAXMIN.aml the maximum and minimum x-coordinate for each polygon
args cover relate.rel
/*relate restore polyarc.rel
relate restore %relate.rel%
/*edit blockexp
edit %cover%
editf label
set all
sv numselect := [show number select]
sv totalpoly := %numselect% + 1
sv count := 2
do %count% le %totalpoly%
/*set blockexp% = %count%
set %cover% = %count%
cursor open
if %:edit.right//amlsnsel% gt 0 &then
  do
    sv maxxcoord := %:edit.right//xmax%
    sv minxcoord := %:edit.right//xmin%
    do &while %:edit.right//amlsnext%
      cursor relate right next
      if %:edit.right//amlsnsel% &then
        do
          sv maxx := %:edit.right//xmax%
          sv minx := %:edit.right//xmin%
          sv maxxcoord := [max %maxxcoord% %maxx%]
          sv minxcoord := [min %minxcoord% %minx%]
        send
        sv imax := %:edit.left//amlsnsel%
        do
          do
            sv imaxxcoord := %:edit.left//xmax%
            sv iminxcoord := %:edit.left//xmin%
            do &while %:edit.left//amlsnext%
              cursor relate left next
              if %:edit.left//amlsnsel% &then
                do
                  sv lmaxx := %:edit.left//xmax%
                  sv lminx := %:edit.left//xmin%
                  sv lmaxxcoord := [max %lmaxxcoord% %lmaxx%]
                  sv lminxcoord := [min %lminxcoord% %lminx%]
                send
                sv lmax := %lmaxxcoord%
                sv lmin := %lminxcoord%
                send
                sv pmax := [max %pmax% %lmax%]
                sv pmin := [min %pmin% %lmin%]
              send
              else
                do
                  sv pmax := %pmax%
                  sv pmin := %pmin%
                send
              send
            else
              do
                if %:edit.left//amlsnsel% &then
                do
                  sv lmaxxcoord := %:edit.left//xmax%
                send
&sv lminxcoord := %edit.left//xmin%
&do &while %edit.left//aminsnext%
cursor relate left next
&if %edit.left//aminsnext% &then
&do
&sv lmaxx := %edit.left//xmax%
&sv lminx := %edit.left//xmin%
&sv lmaxxcoord := [max %lmaxxcoord% %lmaxx%]
&sv lminxcoord := [min %lminxcoord% %lminx%]
&end
&sv lmax := %lmaxxcoord%
&sv lmin := %lminxcoord%
&end
&sv pmax := %lmax%
&sv pmin := %lmin%
&end
&sv xlength := %pmax% - %pmin%
&sv :edit.pxmax := %pmax%
&sv :edit.pxmin := %pmin%
&sv :edit.xlength := %xlength%
cursor close
&sv count := %count% + 1
&end
save
&return
Program YPOLYMAXMIN2.aml

/* Program YPOLYMAXMIN2.aml the maximum and minimum y-coordinate for each polygon */

/* The maximum and minimum y-coordinates for each polygon */

$sv numselect := [show number select]
$sv totalpoly := $numselect + 1
$sv count := 2
$do $while $count le $totalpoly
/* sel blockexp */
$sv cover := $count
$do $while $sel blockexp = $count
$sel $cover := $count
$cursor open

if $edit.right/aml$nse1% gt 0 then
$do
$sv maxycoord := $edit.right/ymax%
$sv minycoord := $edit.right/ymin%
$do $while $edit.right/aml$nex1%
$cursor relate right next
if $edit.right/aml$nex% then
$do
$sv maxy := $edit.right/ymax%
$sv miny := $edit.right/ymin%
$sv maxycoord := [max $maxycoord $maxy%]
$sv minycoord := [min $minycoord $miny%]
$send
$send
$sv max := $maxycoord% $max $minycoord% $min
$send
if $edit.right/aml$nse1% gt 0 then
$do
$sv lmaxycoord := $edit.left/ymax%
$sv lminycoord := $edit.left/ymin%
$do $while $edit.left/aml$nex1%
$cursor relate left next
$do $edit.left/aml$nex% then
$do
$sv lmaxy := $edit.left/ymax%
$sv lminy := $edit.left/ymin%
$sv lmaxycoord := [max $lmaxycoord $lmaxy%]
$sv lminycoord := [min $lminycoord $lminy%]
$send
$send
$sv lmax := $lmaxycoord% $lmax $lminycoord% $lmin
$send
$else
$sv pm := $max $lmax% $lmax%
$sv pm := $min $lmin% $lmin%
$send
$end
$else
if $edit.left/aml$nse1% gt 0 then
$do
$sv lmaxycoord := $edit.left/ymax%
Ssv lminycoord := %:edit.left//ymin%
Sdo $while %:edit.left//aml$next% $cursor relate left next
  $if %:edit.left//aml$next% $then
    $do
      Ssv lmaxy := %:edit.left//ymax%
      Ssv lminy := %:edit.left//ymin%
      Ssv lmaxycoord := [max %lmaxycoord% %lmaxy%]
      Ssv lminycoord := [min %lminycoord% %lminy%]
    $end
  $end
Ssv lmax := %lmaxycoord%
Ssv lmin := %lminycoord%
Send
Ssv pmax := %lmax%
Ssv pmin := %lmin%
SEnd

Ssv ylength := %pmax% - %pmin%
Ssv :edit.pymax := %pmax%
Ssv :edit.pymin := %pmin%
Ssv :edit.ylength := %ylength%
cursor close
Ssv count := %count% + 1
Send
Ssave
Sreturn
/* Program LABELCOORD.AML to extract x and y coordinates of label points */
/* in a coverage. */
/* The coordinate values are place in a coverage PAT */
/* The program take the coverage name as a argument */
args cover
/* arcedit */
/* display 9999 3 */
edit %cover%
editf label
select all
%sv ln := 1 /* ln represent the label number */
do endwhile %ln% le [show number select]

/* Extract x & y coordinates for label points */
%sv xcoord := [extract 1 [show label %ln% coordinate ]]
%sv ycoord := [extract 2 [show label %ln% coordinate ]]

select %cover% = %ln%
calculate x-coord = %xcoord%
calculate y-coord = %ycoord%
%sv ln := %ln% + 1
select all
@end
save
@return
/* Program NODECOORD.AML to extract x and y coordinates of node points */
/* in a coverage. */
/* The coordinate values are placed in a coverage NAT */
/* The program takes the coverage name as an argument */
Sargs cover
/* arcedit */
/* display 9999 3 */
edit %cover%
edit node
select all
Ssv n := 1  /* n represents the node number */
&do &while %n% le [show number select]
/* Extract x & y coordinates for node points */
Ssv xcoord := [extract 1 [show node %n% coordinate ]]
Ssv ycoord := [extract 2 [show node %n% coordinate ]]
select %cover% = %n%
calculate x-coord = %xcoord%
calculate y-coord = %ycoord%
Ssv n := %n% + 1
select all
&end
save
$return
/* Program THICKNESS.AML 
/* Determine the thickness of each soil layer in the soil profile 
/* edit soil.dat - information for the entire soil profile 
/* Soil properties for the first layer of soil 
edit soil.prop info
sel all
sv totalsel := (show number select)
sv count := 1
cursor open
sv depth1 := %edit.depth%
sv soilseries1 := %edit.soil-series%
sv th := %depth1%
sv :edit.THICKNESS := %th%
/* do while %edit.aml$next%
do while %count% le %totalsel%
cursor next
if %edit.aml$next% then
do
/* cursor next
sv depthnew := %edit.depth%
type %depthnew%
sv soilseries2 := %edit.soil-series%
if %soilseries2% eq %soilseries1% then
  do
    sv th := %depthnew% - %depth1%
    sv :edit.THICKNESS := %th%
    sv depth1 := %depthnew%
  end
else
  do
    sv depth1 := %edit.depth%
    sv soilseries1 := %edit.soil-series%
    sv th := %depth1%
    sv :edit.THICKNESS := %th%
  end
end
dv count := %count% + 1
dv return
/* BTESTRICH1.AML */
/* Program to determine the surface characteristics for each land surface */
/* polygon and the gutter characteristics that would connect the surface polygon */
/* to the nearest inlet. These characteristics are written to a file that are */
/* later use to calculate runoff hydrograph from each lot to a known destination/* point. */
/* Program take basin characteristics from the ARC/INFO database and use it */
/* as input to a C program to determine the runoff. */

/* Open file for data */
$sv closestat := [close -all]
$sv lpoly := [open btestpoly.dat openstat -a]
/* Check if file was opened successfully */
$if %openstat% ne 0 $then
   return $inform Could not open file
$end

edit btestinlet
editf label
sel all

/* Assume we know the following:- */
/* 1) Number of inlet on the south side or north side of block */
/* for example, for this test there are 4 inlet on the south side and */
/* 5 on the north side. */
/* 2) The inlet nearest to the final destination point on the south side is */
/* inlet label 17 and furthest away is inlet label 20. */
/* 3) Start with the nearest inlet. */

/* For inlets on the south side of block */
$sv southeqtotalinlet := 4
/* Identify the final destination inlet */
$sv destin := %destin%
$sv destin := 25
$sv destin-id := [extract 1 [show label %destin% id]]
$sv dest-x := [extract 1 [ show label %destin% coordinate]]
$sv dest-y := [extract 2 [ show label %destin% coordinate]]
$sv prin := %destin%
$sv preinlet-id := %dest-id%
$sv preinlet-x := %dest-x%
$sv preinlet-y := %dest-y%

/* Number of inlets on south side equal to 4 */
$sv numberinlet := 1
/* Identify newinlet or nearest inlet */
$sv newin := 17
$sv ln := %newin%
$do while %numberinlet% le %southeqtotalinlet% + 1

$sv inlet-id := [extract 1 [show label %ln % id]]
$sv inlet-x := [extract 1 [ show label %ln % coordinate]]
$sv inlet-y := [extract 2 [ show label %ln % coordinate]]

/* Write -99999 as a indication that the new row is a inlet and */
/* all subsequent rows until a next -39999 is reach are polygons */
/* contributing to that inlet. */
$sv indicator := -99999
$sv writestat := [write %lpoly% %indicator%]
Sav preinletchar := %preinlet-x %preinlet-y
Sav writeatc := (write %lpoly% [quote %preinletchar%])

/* Get the characteristics for storm drain
/* mdinlet is the furthest away inlet from the destination inlet.
Sav mdinlet := 20
Sif %prein% ne %mdinlet% sthen
Srun bteststorm.aml %prein% %ln%
relate restore slope.rel
edit btestfinal
edit label

/* Find the characteristics of the gutter that would take water from overland
/* to the inlet.
Sav bblockdiv-id eq 6
do
cursor open
Sav shape := TRIANG
S/* Sav gdsideslopep := 1.0
Sav zg := 1.0
Sav gpercentslope := %edit.STSLOPE//mean-percent_slope%
Sif gpercentslope gt 0 sthen
S/* Sav galope := gpercentslope / 100.0
Sav sg := gpercentslope / 100.0
else
Sav sg := 0.1 / 100.0
S/* Sav groughness := %edit.ROUGHNESS%
Sav ng := %edit.ROUGHNESS%
S/* Sav gutterwidth := 0.0
Sav wg := 0.0
cursor close
select btestfinal-id = 29
cursor open
Sav south-pminy := %edit.pmin%
cursor close
select blockboundary-id = 1

/* sel pxmin le %inlet-x% and pymax ge %inlet-y%
Sif %prein% eq 20 sthen
reselct pxmin le %preinlet-x% and pymax ge %preinlet-y%
else
reselct pxmin le %preinlet-x% and pymax ge %preinlet-y%
else
Sav numberselect := [show number select]
Sif numberselect gt 0 sthen
S/* Get the characteristics of overland polygons that satisf y these conditions
do
cursor open
Sav bblockdiv-id := %edit.bblockdiv-id%
Sav poly% := %edit.BTESTFINAL%
Sav poly-id := %edit.BTESTFINAL-Id%
Sav surface := %edit.wpscl//surface%
/* check to see if there is missing surface value if so it in edit table for
/* pavement
Sif [null %surface%] sthen
Sav surface := %edit.surface%
Sav flowlength := %edit.YIELD-
Sav polywidth := %edit.YIELD-WIDTH%
156

\[\text{if } \text{blockdiv-id} \; \text{eq} \; 6 \; \text{or} \; \text{blockdiv-id} \; \text{eq} \; 7 \; \text{then}\]

\[
\text{do}\]

\[
\text{av flowlength} \; := \; \%:edit.XLENGTH\%
\]

\[
\text{av polywidth} \; := \; \%:edit.XHYD-WIDTH\%
\]

\[
\text{end}\]

\[
\text{av percentalslope} \; := \; \%:edit.BTSLOPE//MEAN-PERCENT_SLO\%
\]

\[
\text{if } \%\text{percentalslope} \; \text{eq} \; 0 \; \text{then}\]

\[
\text{av percentalslope} \; := \; 0.1
\]

\[
\text{/*}\]

\[
\text{av overlandslope} \; := \; \%\text{percentalslope} / 100.0
\]

\[
\text{av so} \; := \; \%\text{percentalslope} / 100.0
\]

\[
\text{av landroughness} \; := \; \%:edit.WPSOIL//ROUGHNESS\%
\]

\[
\text{av no} \; := \; \%:edit.WPSOIL//ROUGHNESS\%
\]

\[
\text{if } \%\text{no} \; \text{eq} \; 0 \; \text{then}\]

\[
\text{av no} \; := \; \%:edit.XHYD-WIDTH\%
\]

\[
\text{av cn2} \; := \; \%:edit.CN2\%
\]

\[
\text{av hydcond} \; := \; \%:edit.WPSOIL//HYD-CONDUCTIVITY\%
\]

\[
\text{av upperlimit} \; := \; \%:edit.WPSOIL3//HYD-CONDUCTIVITY\%
\]

\[
\text{av ul} \; := \; \%:edit.WPSOIL3//prop2//upper-limit\%
\]

\[
\text{av pymin} \; := \; \%:edit.PYMIN\%
\]

\[
\text{av pxmin} \; := \; \%:edit.PXMIN\%
\]

\[
\text{av pymax} \; := \; \%:edit.PYMAX\%
\]

\[
\text{av pxmax} \; := \; \%:edit.PXMAX\%
\]

\[
\text{if } \%\text{pymin} \; \text{gt} \; \%\text{inlet-y} \; \text{then}\]

\[
\text{av lo} \; := \; \%\text{flowlength} + \%\text{pymin} - \%\text{inlet-y}\%
\]

\[
\text{else}\]

\[
\text{av lo} \; := \; \%\text{flowlength}\%
\]

\[
\text{if } \%\text{pxmin} \; \text{lt} \; \%\text{preinlet-x} \; \text{then}\]

\[
\text{av lg} \; := \; \%\text{preinlet-x} - \%\text{pxmin}\%
\]

\[
\text{else}\]

\[
\text{curator close}\]

\[
\text{av lpolychar} \; := \; \%\text{polychar} // \%\text{surface} // \%\text{lo} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no} // \%\text{no}\%
\]

\[
\text{av gutterchar} \; := \; \%\text{gat} // \%\text{gat} // \%\text{gat} // \%\text{gat} // \%\text{shape}\%
\]

\[
\text{av writestat} \; := \; \text{[write } \%\text{lpoly} \text{ [quote } \%\text{lpolychar} ]\text{]}
\]

\[
\text{av writestat} \; := \; \text{[write } \%\text{lpoly} \text{ [quote } \%\text{gutterchar} ]\text{]}
\]

\[
\text{send}\]

\[
\text{//else} \text{ /* select the next inlet and repeat the above steps} \]

\[
\text{else if } \%\text{numberselect} \; \text{eq} \; 0 \; \text{then}\]

\[
\text{do}\]

\[
\text{edit breathinlet}\]

\[
\text{editf label}\]

\[
\text{sel all}\]

\[
\text{av prein} \; := \; \%\text{inlet}\%
\]

\[
\text{av preinlet-id} \; := \; \%\text{inlet-id}\%
\]

\[
\text{av preinlet-x} \; := \; \%\text{inlet-x}\%
\]

\[
\text{av preinlet-y} \; := \; \%\text{inlet-y}\%
\]

\[
\text{end}\]

\[
\text{else}\]

\[
\text{end}\]

\[
\text{end}\]

\[
\text{//av closestat} \; := \; \text{[close } \%\text{lpoly} \text{]}\]

\[
\text{send}\]

\[
\text{if } \%\text{numberselect} \; \text{ne} \; 0 \; \text{then}\]

\[
\text{do}\]
&do &while %:edit.AMLS NEXT%  
cursor next  
&if %:edit.AMLS NEXT% &then  
&do  
&sv blockdiv-id := %:edit.bbblockdiv-id%  
&sv poly#: := %:edit.BSTFINAL#  
&sv poly-id := %:edit.BSTFINAL-ID%  
&sv surface := %:edit.wpsoil//surface%  
/* check to see if there is missing surface value if so it in edit table for pavement  
&if (null %surface%) &then  
&sv surface := %:edit.surface%  
&sv flowlength := %:edit.YLENGTH%  
&sv polywidth := %:edit.XHYD-WIDTH%  
&if blockdiv-id% eq 6 or %blockdiv-id% eq 7 &then  
&do  
&sv flowlength := %:edit.YLENGTH%  
&sv polywidth := %:edit.xhyd-width%  
&end  
&sv percentalope := %:edit.BTSLOPE//MEAN-PERCENT_SLO%  
&if %percentalope% eq 0 &then  
&sv percentalope := 0.1  
/*   &sv overlandalooe := %:edit.XHYD-WIDTH% / 100.0  
&sv no := %:edit.ROUGHNESS% / 100.0  
/*   &sv hydcond := %:edit.wpsoil3//HYD-CONDUCTIVITY%  
&sv upperlimit := %:edit.wpsoil3//prop2//upper-limit%  
&sv pymin := %:edit.PYMIND%  
&sv pymax := %:edit.PYMAX%  
&sv pxmin := %:edit.PXMIN%  
&sv pxmax := %:edit.PXMAX%  
&if %pymin% gt %inlet-y% &then  
&sv totalflowlength := %flowlength% + %pymin% - %inlet-y%  
&else  
&sv lo := %flowlength%  
&if %pxmin% lt %preinlet-x% &then  
&sv gutterlength := %preinlet-x% - %pxmin%  
&sv lg := %preinlet-x% - %pxmin%  
/*    cursor close  
&else /* select the next inlet and repeat the above steps  
/* Write data to a file  
&sv ipolychar := %poly% %surface% %left %total %foot %not -  
&sv gutchar := %left %total %foot %not %shape%  
&sv writeat := [write %ipoly% [quote %polychar%]]  
&sv writeat := [write %ipoly% [quote %gutchar%]]
```plaintext
send
send

cursor close
edit bestinlet
editf label
sel all

身处 preln := %ln%
身处 preinlet-id := %inlet-id%
身处 preinlet-x := %inlet-x%
身处 preinlet-y := %inlet-y%

/*
身处 numberinlet := %numberinlet% + 1
/*
身处 ln := %ln% + 1
send

身处 numberinlet := %numberinlet% + 1
身处 ln := %ln% + 1
/* End do while loop for less than or equal to southtotalinlet
end

身处 closestat := (close %poly%)

return
```
/*TESTSTORM.AML*/

Program to select arcs that represent stormdrain which connect an inlet to a
destination point. Decision are made based on the coordinates of the arc
nodes and inlet and destination coordinates.

args preln inlet
edit btestinlet
select all
sav .dest-id := [ extract 1 [ show label %preln% id ] ]
sav .dest-x := [ extract 1 [ show label %preln% coordinate ] ]
sav .dest-y := [ extract 2 [ show label %preln% coordinate ] ]
sav .inlet-id := [ extract 1 [ show label %ln% id ] ]
sav .inlet-x := [ extract 1 [ show label %ln% coordinate ] ]
sav .inlet-y := [ extract 2 [ show label %ln% coordinate ] ]
edit btestdrain
editf arc
select all
sav an := 1 /* an represent the arc number*/
sav count := 1 /* count the number of connected arcs to destination*/
do do while %an% le [show number select]
    sav fnode-x := [extract 1 [show arc %an% nodes]]
sav fnode-y := [extract 2 [show arc %an% nodes]]
sav tnode-x := [extract 3 [show arc %an% nodes]]
sav tnode-y := [extract 4 [show arc %an% nodes]]
    do if %fnode-x% eq %inlet-x% and %tnode-x% eq %dest-x% then
        sav arcnumber := %an%
        srun btestdrain.mal %arcnumber% %preln% %ln%
        sav an := %an% + 1
        end
    else if %fnode-x% eq %dest-x% and %tnode-x% eq %inlet-x% then
        do sav arcnumber := %an%
        srun btestdrain.mal %arcnumber% %preln% %ln%
        sav an := %an% + 1
        end
    else
        sav an := %an% + 1
    end
end
sreturn
/* BTESTDRAIN.AML */
/* Program to obtain storm drain characteristics from the drainage attribute */
/* table. These values are written to a file called stormdrain.dat. */

/* Extract the characteristics of the stormdrains (arcs) from the */
/* stormdrain attribute table */

$args arcnumber preln ln

relate restore slope.rel

edit btestdrain
edit arc
Sel btestdrain# eq %arcnumber%

cursor open

/* $sv length := %:edit.LENGTH%
 $sv lc := %:edit.LENGTH%
 $sv percent_slope := %:edit.STORMSLOPE//MEAN-PERCENT_SLO%
 if $percent_slope eq 0 then
 $sv percent_slope := 0.1
 /* $sv channel_slope := $percent_slope / 100.0
 $sv sc := $percent_slope / 100.0
 /* $sv roughness := %:edit.ROUGHNESS%
 $sv nc := %:edit.ROUGHNESS%
 /* Pipe size is in inches
 $sv pipe_size := %:edit.PIPE-SIZE%
 /* $sv diameter := $pipe_size / 12.0
 $sv wc := $pipe_size / 12.0
 /* $sv side_slope := %:edit.SIDESLOPE%
 $sv sc := %:edit.SIDESLOPE%
 $sv shape := %:edit.SHAPE%

cursor close

/* Write data to a file */
/* $sv closestat := [close -all]
 $sv sdrain := [open btestdrain.dat openstat -a]
 /* Check if file was opened successfully
 $if openstat ne 0 then
 $return $inform Could not open file
 $sv sdrainchar := %preln% %ln% %arcnumber% %lc% %sc% %nc% %wc% %sc% $shape%
 $sv writestat := [write $sdrain$ [quote $sdrainchar]]
 $sv closestat := [close $sdrain$]

sel all

$return
Appendix D: Typical Programs for Routing of the Discharge Hydrographs.

Programs were written in the 'C' programming language.
/* Program to perform kinematic wave routing computations for OVERLAND and CHANNEL surfaces. The program uses the physical characteristics of the drainage areas stored in a spatial database created with a geographic information software called ARC/INFO. Computations are done in English Units.

Input to program are obtained from ARC/INFO database */

float channel();
float excessrain();

void main()
{
  float LO, SO, NO, DXO, DT, T, RAIN[400], ARAIN[400], TIME[400];
  float LC, DC, NC, DXC, SC, WC;
  float h[400][400], Q[400][400] ;
  float B[400][400], C[400][400], D[400][400], E[400][400];
  float M, Ctrl, Alpha, Hydcond, ul, polywidth;
  float chydro[400];

  char shape[10], surface[5];
  char filehydro[400], htemp[20];

  int I, J, NTIM, NXO, NXC, count, code, inietnum, preinletnum, polynum;


  /* Initialize the array RAIN to zero */
  for (J = 0; J < 400; J++)
    RAIN[J] = 0.0;

  /* Initialize the array chydro to zero */
  for (J = 0; J < 400; J++)
    chydro[J] = 0.0;

  /* Input of Overland Flow parameters */
  /* Overland flow parameters from spatial database thru arc or arcedit*/
  /* Enter overland flow path length in feet */
  /* Enter overland flow distance increment in feet */
  /* Enter overland flow slope in ft/ft */
  /* Enter overland flow roughness */

  /* Input time parameters and rainfall duration */
  /* Enter total time for simulation in minutes */
  /* Enter time increment in minutes*/

  /* Input of channel flow parameters */
  /* Enter channel length in feet */
  /* Enter channel distance increment in feet */
  /* Enter channel slope ft/ft */
  /* Enter channel Roughness */
  /* Enter channel width or diameter in feet */
  /* Enter channel shape: RECT; CIRC; SQUARE; TRIANG, TRAP */
Enter 'Z' for channel sideslope where Horiz:Vert is 2:1
('Z' is zero for shape RECT, CIRC, or SQUARE)

*/

princf("Enter total time for simulation in minutes \n");
scanf("%f", &T);

princf("Enter time increment in minutes\n");
scanf("%f", &DT);

T = T * 60.0;
DT = DT * 60.0;
NTIM = (T/DT);

princf("Enter number of interval for DELTAX for overland\n");
scanf("%d", &NXO);

princf("Enter number of interval for DELTAX channel\n");
scanf("%d", &NXC);

princf("Enter antecedent condition code: 1, 2, 3\n");
scanf("%d", &code);

/* READ WATERSHED CHARACTERISTICS FROM A FILE THAT HOLDS INFORMATION
  OBTAIN FROM THE SPATIAL DATABASE */

fdata = fopen("landpoly.dat", "r");

/* Parameter for overland and gutter or channel flow */
count = 1;
while ( fscanf (fdata, "%d%f%f", &inletnum) == EOF )
  
while (polynum != -99999)
  
if ( fscanf (fdata, "%d", &polynum) == EOF )
  
if ( strcmp(surface, "IMP") == 0 )
    fpt = fopen("rain2-data", "r");
  else
    excessrain(cn2, hydcond, ul, code);
  
if (fpt == NULL)
    prinfs("\n ERROR - Cannot open the designated file \n");

I = 0;
/* Input time in minutes and rainfall in in/hr */
while ((fscanf(fpc,"%£ %f
", STIME[I], &RAIN[I]) != EOF)
/* convert time to seconds */
TIME[I] = TIME[I] * 60.0;
/* convert rainfall in in/hr to ft/sec */
RAIN[I] = RAIN[I]/43200.0;
fprintf(frain,"%d \t %f \t %£ 
", I, TIME[I], RAIN[I]);
++I;
}
TIME[I] = TIME[I-1] + DT;
while(TIME[I] <= T){
RAIN[I] = 0.0;
fprintf(frain,"%d \t %f \t %£ 
", I, TIME[I], RAIN[I]);
++I;
}
}
fclose(fpc);
fclose(frain);
/* Calculate overland flow */
/* Calculate ALPHA and set M = 5/3 */
ALPHA = 1.486 * sqrt((double)(SO))/NO ;
M = 5.0/3.0 ;
/* Use standard form of Finite Difference equation */
DXO = ( LO /(float) NXO);
/*Write headings for overland flow output */
fpo = fopen("overland3.out","w") ;
/* fprintf(fpo,"\n Overland flow length - %.4f £eet\n",LO);
fprintf(fpo,"\n Overland distance increment - %.4f feet\n",DXO);
fprintf(fpo,"\n Overland slope - %.4f ft/ft\n",SO);
fprintf(fpo,"\n Overland roughness - %.4f\n",NO);
fprintf(fpo,"\n Total simulation time - %.4f minutes\n", (T/60.0));
fprintf(fpo,"\n Time increment - %.4f minutes\n", (DT/60.0));
fprintf(fpo,"\n ALPHA - %.4f\n", ALPHA);
fprintf(fpo,"\n DISTANCE TIME DEPTH FLOW \n");
*/
/* Begin Time Loop */
for(J = 1; J <= NTIM ; J++){
/* Boundary condition at x = 0.0 is h = 0.0, Q = 0.0 for every Time Step */
h[0][J] = 0.0;
QO[0][J] = 0.0;
/* Begin distance loop */
for(I = 1; I <= NXO ; I++){
/* Plane surface is initially dry */
h[I][0] = 0.0;
/* Standard Form */
/* ARAIN[J] = (RAIN[J] + RAIN[J-1]) / 2.0 ;*/
ARAIN[J] = RAIN[J];
S[I][J] = ARAIN[J] * DT + h[I][J-1] ;
C[I][J] = (h[I][J-1] - h[I-1][J-1]) / 2.0 ;
D[I][J] = h[I][J-1] - h[I-1][J-1] ;
h[I][J] = S[I][J] - ALPHA * M * (DT/DXO) * pow((double) C[I][J],(double) (M - 1.0)) * C[I][J];
if (h[I][J] < 0.0)
h[I][J] = 0.0;
QO[I][J] = ALPHA * pow((double) h[I][J],(double) M);
if (QO[I][J] < 0.0)
QO[I][J] = 0.0;

/* Check for numerical stability with stability factor theta, and if
* theta less than unity it is ok to use standard form*/
if (ARAIN(J) == 0)
    THETA = ALPHA * M * pow((double) h[I-1][J-1], (double) (M - 1.0))
    * (DT/DXO);
else
    THETA = (ALPHA / ARAIN(J) * DXO)
    * (pow((double) (ARAIN(J) * DT + h[I-1][J-1]), (double) M)
    - pow((double)h[I-1][J-1], (double) M));

/* If theta is greater than unity, use the Conservation form of the
* finite difference approximation */
if (THETA > 1.0) {
    QO[I][J] = QO[I-1][J] + ARAIN(J) * DXO - (DXO/DT)
    * (h[I-1][J] - h[I-1][J-1]);
    if (QO[I][J] < 0.0)
        QO[I][J] = 0.0;
    h[I][J] = pow((double) (QO[I][J] / ALPHA), (double) (1.0 / M));
}

/* if ((I)*DXO = LO)*/
if (fabs((I)*DXO - LO) < 0.0001) {
    QO[I][J] = polywidth * QO[I][J];
    fprintf(fp, "%f	%f	%e	%e
", (I) *DXO, ( (J)*DT/60.0), h[I][J], QO[I][J]);
}

/*End of Distance loop */
*/End of Time loop */
}
}
fclose(fp);

channel(QO, NXO, LC, NXC, MC, WC, SC, T, DT, shape, count, polynomial, inletnum, preinletnum, chydro);

count = count + 1;
} /* end of if (polynomial != -99999) */
} /* end of second while loop*/
} /* End of while loop */

/* Modification to output last combine hydrograph from polygons */
strcpy(filehydro, "comhydro");
sprintf(htemp, "%d", preinletnum);
strcat(filehydro, htemp);
strcat(filehydro, ".out");

if ((fpcomb = fopen(filehydro, "w")) == NULL)
    printf("unable to open the combine hydrograph output file....\n");
exit(3);
}

/* Write the combined hydrograph to a file previously created with
inletnum as a portion of the filename */
for(J = 0; J < NTIM ; J++)
    fprintf(fpcomb, "%f\t%e
", (J)*DT/60.0, chydro[J]);
}
fclose(fpcomb);

/*----------------------------------------------*/
printf("Preinletnum = %d", preinletnum);
Program to perform kinematic wave routing computations for CHANNEL.
* The program uses the physical characteristics of the drainage
* areas and effective rainfall data stored in a spatial database created
* with a geographic information software called ARC/INFO. Computations
* are done in English Units.
*/

/* Input to program are obtained from ARC/INFO database */
float channel(QO, NXO, LC, NXC, SC, NC, WC, ZC, T, DT, shape, count, polynum, inletnum, preinletnum, chydro)
float h[400][400], AC[400][400], QC[400][400];
float B[400][400], C[400][400], D[400][400], E[400][400];
float THETA, ALPHA, M;
int I, J, NTIM;
char fileout[400], temp[20];
char filehydro[400], htemp[20];
FILE *fpc, *fph;

/* Input of channel flow parameters
Enter channel length in feet
Enter channel distance increment in feet
Enter channel slope in ft/ft
Enter channel Roughness
Enter channel width or diameter in feet
Enter channel shape: RECT; CIRC; SQUARE, TRIANG, TRAP
Enter 'Z' for channel sideslopes where Horz:Vert is 2:1
('Z' is zero for shape RECT, CIRC, or SQUARE)
*/
NTIM = (T/DT);

/* --------Modification to combine hydrographs from polygons */
if (count == 1)
  preinletnum = inletnum;
if (inletnum == preinletnum)
  strcpy(filehydro, "combhydro");
sprintf(htemp, "%d", preinletnum);
strcat(filehydro, htemp);
strcat(filehydro, ".out");
if ((fph = fopen(filehydro, "w")) == NULL)
{
    printf("unable to open the combine hydrograph output file....\n");
    exit(2);
}

/* Write the combined hydrograph to a file previously created with
    inletnum as a portion of the filename */
for(J = 0; J <= NTIM; J++){
    fprintf(fph,"%e\n", ((J)*DT/60.0), chydro[J]);
}
fclose(fph);

/* Re-initialize the array chydro to zero */
for(J = 0; J < 400; J++){
    chydro[J] = 0.0;
}

/* End of if (inletnum == inletnum) */

/* ------vn < i Qg modifications—  ---------------------------------*/
/* Calculate channel flow */
/* Information to create a file with a different name for each polygon output */

strcpy(fileout, "prunoff");
/* sprintf(temp, "id", count);*/
sprintf(temp, "%d", count);
strcat (fileout, temp);
strcat (fileout,".out");

if (( fpc = fopen(fileout, "w")) == NULL) {
    printf("unable to open the output file ......
");
    exit(1);
}

fprintf(fpc,"inletnum = %d
", inletnum);
fprintf(fpc,"Shape = %s
", shape);

if (((strcmp(shape, "RECT")) == 0) || ((strcmp(shape, "rect")) == 0)) {
    ALPHA = (1.486 * sqrt((double)(SC))/ NC)
    * pow((double) (WC), (double) (-2.0/3.0)) ;
    M = 5.0 / 3.0;
}
else if (((strcmp(shape, "CIRC")) == 0) || ((strcmp(shape, "circ")) == 0))
/* If channel is circular the width is the diameter */
    DC = WC;
    ALPHA = (0.804 * sqrt((double)(SC))/ NC)
    * pow((double) (DC), (double) (1.0/6.0)) ;
    M = 5.0 / 4.0;
}
else if (((strcmp(shape, "SQUARE")) == 0) || ((strcmp(shape, "square")) == 0))
    ALPHA = (0.72 * sqrt((double)(SC)) / NC;
    M = 4.0 / 3.0;
}
else if (((strcmp(shape, "TRIANG") == 0) || ((strcmp(shape, "triang")) == 0))
    ALPHA = (0.94 * sqrt((double)(SC))/ NC)
    * pow((double) (ZC/ (1.0 - pow((double) (ZC), (double) (2)) ) , (double) (1.0/3.0) ) ;
    M = 4.0 / 3.0;
}
else if (((strcmp(shape, "TRAP")) == 0) || ((strcmp(shape, "trap") == 0))
    /* for trapezoidal */
}
/* Use standard form of Finite Difference equation */
DXC = ( LC / (float)NXC);

/* Write headings for channel flow output */
fprintf(fpc," ALPHA - %.e 	 M - %.e 
", ALPHA, M);
fprintf(fpc," DISTANCE TIME AREA FLOW 
");

for(J = 1; J <= NTIM; J++) {
    QC[0][J] = QC[NXC][J];
    printf("QC[0][J] = %.f\n", QC[0][J]);
    AC[0][J] = pow ((double)(QC[0][J] / ALPHA), (double)(1.0 / M));
    printf("AC[0][J] = %.f\n", AC[0][J]);
}

/* Begin Time Loop */
for(J = 1; J <= NTIM; J++) {
    QC[0][0] = QC[0][J];
    AC[0][0] = AC[0][J];
    QC[0][J] = QC[0][J];
    AC[0][J] = AC[0][J];

    if (QC[0][J] < 0.0)
        QC[0][J] = 0.0;

    AC[0][J] = pow ((double)(QC[0][J] / ALPHA), (double)(1.0 / M));

    if (fabs((I)*DXC - LC) < 0.0001)
        fprintf(fpc," %f 	%f 	%f 
", (I)*DXC, ((J)*DT/60.0), AC[0][J], QC[0][J]);
}

fclose(fpc);
return;

/* Function to calculate excess rainfall within overland program */
/* A program in 'C' programming language to calculate rainfall excess using the SCS curve number technique with a soil moisture accounting procedure.
Time interval for rainfall is in hour.
Rainfall intensity is in inches per hour.
Cumulative precipitation and cumulative excess precipitation are in inches.
The net rainfall rate is, in/hr. */
float excessrain(cn2, hydcond, ul, code);
float cn2, hydcond, ul;
int code;

float inrain[125], exrain[125], exrate[125], time[125], timeinterval[125];
float cumprecipi[125], ami[125], acre[125], infill[125], cumwater[125];
float s, cnl, c2, c3, inperc, perc, amx;
float raininterval;

int I, ninterval;
FILE *ifrain, *ofrain, *oplot;

/* Input raw rainfall data from file and calculate cumulative precipitation */
ifrain = fopen("rain2.data", "r");
ofrain = fopen("rain2.coext", "w");
oplot = fopen("rainfall.excess", "w");

if(ifrain == NULL)
  printf("\nERROR - cannot open the designated file \n");
else
  I = 1;
/* Input time in minutes and rainfall in in/hr. */
  while((fscanf(ifrain, "%d %d %d
", &time[I], &inrain[I])) != EOF)
    { /* printf("%d\t%f\t%f\t
", I, time[I], inrain[I]); */
      ++I;
    }
  ninterval = I-1;
/* Calculate excess rainfall using the SC3 curve number method */
/* CN2, ul, hydcond , pass in by function call */
/* Input percolation at the rate of hydraulic conductivity, in/hr */
/* Rainfall at 5 minutes interval */
raininterval = 5.0 / 60.0;
  perc = hydcond * raininterval; /* perc in inches */
inperc = perc * 0.3;
/* Calculate CNI from CNII input values */
  if (code == 2)
    cnl = cn2;
  else if (code == 1)
    { c2 = cn2 * cn2;
      c3 = c2 * cn2;
      cnl = (-16.31) + 1.349 * cn2 - 0.31279 * c2 + 0.0001177 * c3;
    }
  else
    printf(" no facility at present for a code of 3\n");
\[ \text{smx} = (1000.0 - 10.0 \times \text{cnl}) / \text{cnl} ; \]

/* Consider that the soil is initially wet at a fraction of total capacity for soil water */

\[ \text{sm}[0] = 0.50 \times \text{ul} ; \]

\[ s = \text{smx} \times ((\text{ul} - \text{sm}[0]) / \text{ul}) ; \]

/* Volume of direct runoff equivalent to the volume of excess rainfall */
/* If rainfall rate less than infiltration rate all the rainfall infiltrate */

\[ \text{cumprecipl}[1] = 0.0 ; \]
\[ \text{accr}[1] = 0.0 ; \]
\[ \text{exrain}[1] = \text{accr}[1] ; \]
\[ \text{exrate}[1] = \text{exrain}[1] ; \]

/* Soil moisture is reduced at half the rate of percolation until saturation */

/* Volume of direct runoff equivalent to the total volume */
/* of excess rainfall */

/* Soil moisture is increased by infiltration and reduced by half the rate of percolation until saturation */

\[ \text{sm}[1] = \text{sm}[1-1] + \text{cumprecipl}[1] - \text{inperc} ; \]
\[ \text{exrain}[1] = \text{accr}[1] ; \]
\[ \text{exrate}[1] = \text{exrain}[1] / \text{timeinterval}[1] ; \]

/* Volume of direct runoff equivalent to the total volume of excess rainfall */
/* perc = hydraulic conductivity \times \text{timeinterval}[1] ; */ /* perc in inches */

\[ \text{sm}[2] = \text{sm}[1-1] + \text{cumprecipl}[1] - \text{inperc} ; \]
\[ \text{exrain}[1] = \text{accr}[1] ; \]
\[ \text{exrate}[1] = \text{exrain}[1] / \text{timeinterval}[1] ; \]

/* Soil moisture is reduced at half the percolation rate until saturation */

if ((\text{cumprecipl}[1] - 0.2 \times s) <= 0.0)

\[ \text{accr}[1] = 0.0 ; \]

/* Soil moisture is reduced at half the percolation rate until saturation */

\[ \text{sm}[1] = \text{sm}[1-1] + \text{cumprecipl}[1] - \text{inperc} ; \]
\[ \text{exrain}[1] = \text{accr}[1] ; \]
\[ \text{exrate}[1] = \text{exrain}[1] / \text{timeinterval}[1] ; \]

/* Output */

\[ \text{fpprintf}\left(\text{ofrain},\text{'%f\t%f\t%f\t%f\t%f\t%f\t%n'},\text{time}[1],\text{inrain}[1],\text{cumprecipl}[1],\text{accr}[1],\text{exrain}[1],\text{exrate}[1]\right) ; \]

\[ \text{fpprintf}\left(\text{oplot},\text{'%f\t%f\t%n'},\text{time}[1],\text{exrate}[1]\right) ; \]

/* Output */

\[ \text{if} (\text{sm}[1] == 0) \]

\[ \text{accr}[1] = ((\text{cumprecipl}[1] - 0.2 \times s) \times (\text{cumprecipl}[1] - 0.2 \times s)) / (\text{cumprecipl}[1] + 0.8 \times s) ; \]

\[ \text{infil}[1] = \text{cumprecipl}[1] - \text{accr}[1] ; \]
\[ \text{sm}[1] = \text{sm}[1-1] - \text{infil}[1] - \text{perc} ; \]
\[ \text{exrain}[1] = \text{accr}[1] - \text{accr}[1-1] ; \]
```c
exrate[I] = exrain[I] / timeinterval[I];
fprintf(ofrain,"%f\t%f\t%f\t%f\t%f\t%f\n", time[I], inrain[I], cumprecipl[I], accre[I], exrain[I], exrate[I]);
fprintf(oplot,"%f\t%f\n", time[I], exrate[I]);
}
else if (sml[I-1] < ul)
{
    accre[I] = (cumprecipl[I]-0.2*s)*(cumprecipl[I]-0.2*s)/(cumprecipl[I]+0.8*s);
    infil[I] = cumprecipl[I] - accre[I];
    sml[I] = sml[I-1] + infil[I] - inperc;
    if ((infil[I]) > 2.0 * perc)
    {
        if (inrain(I) == 0.0)
            accre[I] = accre[I-1];
        else
        sml[I] = sml[I-1] + 2.0 * perc - inperc;
    }
    exrain[I] = accre[I] - accre[I-1];
    exrate[I] = exrain[I] / timeinterval[I];
    fprintf(ofrain,"%f\t%f\t%f\t%f\t%f\t%f\n", time[I], inrain[I], cumprecipl[I], accre[I], exrain[I], exrate[I]);
    fprintf(oplot,"%f\t%f\n", time[I], exrate[I]);
}
else if (sml[I-1] > ul)
{
    /* If soil water more available soil water storage capacity, more water available for runoff */
    sml[I-1] = ul;
    s = smx * ((ul - sml[I-1])/ul);
    accre[I] = (cumprecipl[I]-0.2*s)*(cumprecipl[I]-0.2*s)/(cumprecipl[I]+0.8*s);
    infil[I] = cumprecipl[I] - accre[I];
    sml[I] = sml[I-1] + infil[I] - perc;
    exrain[I] = accre[I] - accre[I-1];
    exrate[I] = exrain[I] / timeinterval[I];
    fprintf(ofrain,"%f\t%f\t%f\t%f\t%f\t%f\n", time[I], inrain[I], cumprecipl[I], accre[I], exrain[I], exrate[I]);
    fprintf(oplot,"%f\t%f\n", time[I], exrate[I]);
}
fclose(ifrain);
fclose(ofrain);
fclose(oplot);
return;
}
```
/* Program to perform kinematic wave routing computations for
CHANNEL. The program uses the physical characteristics of
the drainage areas stored in a file that obtain its value from a spatial
database created with a geographic information system software called
ARC/INFO. Computations are done in English Units
*/

#include <stdio.h>
#include <math.h>
#include <string.h>
#include <sys/types.h>
#include <sys/stat.h>

float chanroutO;

void main()
{
    float DT, T;
    float LC, DC, SC, NC, WC;
    float QO[400][400];
    float B[400][400], C[400][400], D[400][400], E[400][400];
    float THETA, ALPHA, M, UNITS;
    char shape[10], surface[5];
    int I, J, NTIM, NXd, NXC, count, inletnum, polynum;
    int preinletnum, arcnmber;

    FILE *fdata, *fps;

    printf("Enter total time for simulation in minutes \n");
    scanf(\n%f", &T);

    printf("Enter time increment in minutes\n");
    scanf("\n%f", &DT);

    T = T * 60.0;
    DT = DT * 60.0;
    NTIM = (T/DT);

    /*
    printf("Enter number of interval for DELTAX for overland\n");
    scanf("\n%d", &NXO);
    */

    printf("Enter number of interval for DELTAX channel\n");
    scanf("\n%d", &NXC);

    /* READ STREAM DRAIN CHARACTERISTICS FROM A FILE THAT HOLDS INFORMATION
    OBTAIN FROM THE SPATIAL DATABASE */

    fdata = fopen("southdrain.dat", "r");

    /* Parameter for overland and gutter or channel flow */
    count = 1;

    while((fscanf(fdata,"\d\d\d\d\d\d\n", &preinletnum) != EOF))
    {
        fscanf(fdata,"\d\d\d\d\d\d\n", &inletnum, &arcnumber, &LC, &SC, &NC, &WC, &shape);

    /*...*/
chanrout(QO, NXO, LC, NC, SC, WC, ZC, T, DT, shape, count, preinletnum, inletnum);

    count = count + 1;
} /* End of while loop */

return;

/* Function chanrout */
/* Program to perform kinematic wave routing computations for CHANNEL. 
* The program uses the physical characteristics of the drainage 
* areas and effective rainfall data stored in a spatial database created 
* with a geographic Information software called ARC/INFO. Computations 
* are done in English Units. */
/* Input to program are obtained from ARC/INFO database */
float chanrout(QO, NXO, LC, NC, SC, WC, ZC, T, DT, shape, count, preinletnum, inletnum)
float QO[400][400];
float LC, ZC, SC, NC, WC, DT, T;
float DC, DXC;
float TIME[400], AC[400][400], QC[400][400], AQO[400][400];
float B[400][400], C[400][400], D[400][400], E[400][400];
float THETA, ALPHA, M, UNITS;
char fileout[400], temp[20], filein[400], ctemp[20];
int count, NXO, NC, preinletnum, inletnum;

FILE *fpc, *fupstr;
/* In English units */
UNITS = 1.486;
/* Input of channel flow parameters 
    Enter channel length in feet 
    Enter channel distance increment in feet 
    Enter channel slope in ft/ft 
    Enter channel Roughness 
    Enter channel width or diameter in feet 
    Enter channel shape: RECT, CIRC; SQUARE, TRIANG, TRAP 
    Enter 'Z' for channel sideslope where Horiz/Vert is Z:1 
    ('Z' is zero for shape RECT, CIRC, or SQUARE) */
/* Input time parameters 
    Enter total time for simulation, T 
    Enter time increment, DT */
NTIM = (T/DT);
/* Calculate channel flow */
/* Information to create a file with a different name for each inlet output */
strcpy(fileout, "shrunoff");
sprintf(temp, "%d", preinletnum);
strcat(fileout, temp);
strcat(fileout, ".out");

printf("Count = %d\n", count, preinletnum);
// Calculate ALPHA and M for various channel shapes */
if (fpc = fopen(fileout, "w") == NULL) {
    printf("unable to open the output file .......
");
    exit(1);
}
/* fprintf(fpc,"\nShape = %s\n", shape);*/
if (((strcmp(shape, "RECT") == 0) || ((strcmp(shape, "rect") == 0)))
    ALPHA = (UNITS * sqrt((double)(SC)) / NC)
    * pow((double)(WC), (double)(-2.0/3.0));
    M = 5.0 / 3.0;
else if (((strcmp(shape, "CIRC") == 0) || ((strcmp(shape, "circ") == 0)))
    /* If channel is circular the width is the diameter */
    DC = WC;
    ALPHA = (0.804 * sqrt((double)(SC)) / NC)
    * pow((double)(DC), (double)(1.0/6.00));
    M = 5.0 / 4.0;
else if (((strcmp(shape, "SQUARE") == 0) || ((strcmp(shape, "square") == 0)))
    ALPHA = (0.72 * sqrt((double)(SC)) / NC)
    * pow((double)(DC), (double)(1.0/3.0));
    M = 4.0 / 3.0;
else if (((strcmp(shape, "TRIANG") == 0) || ((strcmp(shape, "triang") == 0)))
    ALPHA = (0.94 * sqrt((double)(SC)) / NC)
    * pow((double)(ZC/ (1.0 + pow((double)(ZC), (double)(2)))), (double)(1.0/3.0));
    M = 4.0 / 3.0;
else if (((strcmp(shape, "TRAP") == 0) || ((strcmp(shape, "trap") == 0)))
    /* for trapezoidal */
}
/*Use standard form of Finite Difference equation */
/*
    NXC = (LC/DXC);
    DXC = (LC / (float)(NXC));
    printf("DXC = %f\n",DXC);
*/
/*Write headings for channel flow output */
/* fprintf(fpc,"\n ALPHA = %4.4f M = %4.4f \n", ALPHA, M);*/
/* fprintf(fpc,"\n DISTANCE TIME AREA FLOW \n");*/
/* Open file of overland flow hydrograph and combine it with channel flow*/
strncpy(filein, "combhydroricalue3984");
sprintf(chtemp, "%d", inletnum);
strcat(filein, ctemp);
strcat(filein, ".out");
strncpy(chfilein, "crunanoffricalue3984");
sprintf(chtemp, "%d", inletnum);
strcat(chfilein, ctemp);
strcat(chfilein, ".out");
strncpy(ocfileout, "ochydroricalue3984");
sprintf(octemp, "%d", inletnum);
strcat(ocfileout, otemp);
strcat(ocfileout, ".out");
/* Or open channel file and continue routing */

if (count == 1)
{
    if (fupstr == fopen(filein, "r")) == NULL)
        printf("ERROR - cannot open combined input hydrograph file...
");
    else
    {
        J = 0;
        while((fscanf(fupstr, "%f\n", &TIME[J], &QC[0][J])) != EOF)
        {
            TIME[J] = TIME[J] * 60.0;
            AC[0][J] = pow((double)(QC[0][J] / ALPHA), (double)(1.0 / M));
            ++J;
        }
        fclose(fupstr);
    }  
else if (count > 1)
{
    if (stat (filein, &buf) == 0)
    {
        combinlet(T, DT, inletnum);
        if ((fupstr = fopen(outfileout, "r")) == NULL)
            printf("ERROR - cannot open combined outlet hydrograph file...
");
        else
        {
            J = 0;
            while((fscanf(fupstr, "%f\n", &TIME[J], &QC[0][J])) != EOF)
            {
                TIME[J] = TIME[J] * 60.0;
                AC[0][J] = pow((double)(QC[0][J] / ALPHA), (double)(1.0 / M));
                ++J;
            }
            fclose(fupstr);
        }
    
    else
    {
        if ((fupstr = fopen(chfilein, "r")) == NULL)
            printf("ERROR - cannot open combined input hydrograph file...
");
        else
        {
            J = 0;
            while((fscanf(fupstr, "%f\n", &TIME[J], &QC[0][J])) != EOF)
            {
                TIME[J] = TIME[J] * 60.0;
                AC[0][J] = pow((double)(QC[0][J] / ALPHA), (double)(1.0 / M));
                ++J;
            }
            fclose(fupstr);
        }
    }

    /*
    Begin Time Loop
    */
    J = 0;
if (J == 0)
    fprintf(fpc, "%f\t%e\n", (J)*DT/60.0, QC[0][J]);

for(J = 1; J <= NTIM ; J++)
    /* Boundary condition at x = 0.0 for every Time Step */
    /* Read in hydrograph from upstream channel or Combined hydrograph for
      overland and channel flow. */
    /* If no direct overland flow into the channel */
    QO[NXO][J] = 0.0;

    /* Begin distance loop */
    for(I = 1; I <= NXC ; I++)
        /* Standard Form */
        B[I][J] = AQO[NXO][J] * DT - AC[I][J-1];
        C[I][J] = (AC[I][J-1] + AC[I-1][J-1]) / 2.0;
        D[I][J] = AC[I][J-1] - AC[I-1][J-1];
        AC[I][J] = B[I][J] - ALPHA * M * (DT/DXC);
        if (AC[I][J] < 0.0)
            AC[I][J] = 0.0;
        QC[I][J] = ALPHA * pow((double) AC[I][J], (double) M);

        /* Check for numerical stability with stability factor theta, and if
         * theta is less than unity is ok to use standard form*/
        if (AQO[NXO][J] == 0)
            THETA = ALPHA * M * pow((double) AC[I-1][J-1], (double) (M - 1.0))
            * (DT/DXC);
        else
            THETA = (ALPHA / (AQO[NXO][J] * DXC))
            * (pow((double) (AQO[NXO][J] * DT + AC[I-1][J-1]), (double) (M))
            - pow((double) (AC[I-1][J-1]), (double) (M)));

        /* If theta is greater than unity, use the Conservation form of the
         * finite difference approximation */
        if (THETA > 1.0)
            QC[I][J] = QC[I][J-1] + AQO[NXO][J] * DXC - (DXC/DT)
            * (AC[I-1][J] - AC[I-1][J-1]);
        if (QC[I][J] < 0.0)
            QC[I][J] = 0.0;
        AC[I][J] = pow((double) QC[I][J] / ALPHA, (double) (1.0 / M));

    /* if ((I)*DXC == LC) */
    /* printf("%f\n", (I)*(DXC), LC); */
    /* if (fabs((I)*DXC - LC) < 0.001) */
*/fprintf(fpc, "%f\t%e\n", (I)*DT/60.0, QC[I][J]);*/
    fclose(fpc);
    return;

/* Function main */
/* Program to combined hydrographs at a common inlet. */

combinlac(T, DT, inletnum)
int inletnum;
float DT, T;

| float time[400];
float ohydro[400], chydro[400], ochydro[400];

int I, J, NTIM;
char filein[400], ctemp[20], chfilein[400], chtemp[20];
char ofileout[400], octemp[20];

FILE *fpa, *fpa, *fpcomb;
T = T * 60.0;
DT = DT * 60.0;
NTIM = (T/DT);

/*Initialize the array hydro to */
for(J = 0; J < 400; J++)
| ochydro[J] = 0.0;

/* Combine hydrograph for overland flow and channel upstream flow at inlet */

strcpy(filein, "combhydro");
sprintf(ctemp, "%d", inletnum);
strcat(filein, ctemp);
strcat(filein, "\n");

strcpy(chfilein, "chrunoff");
sprintf(chtemp, "%d", inletnum);
strcat(chfilein, chtemp);
strcat(chfilein, "\n");

strcpy(ofileout, "ochydro");
sprintf(octemp, "%d", inletnum);
strcat(ofileout, octemp);
strcat(ofileout, "\n");

if((fpa = fopen(filein, "r")) == NULL)
| printf("unable to open file for overland flow hydrograph......\n");
| J = 0;

while((fscanf(fpa, "%f%e\n", &time[J], &ohydro[J]) != EOF)
| ++J;
| fclose(fpa);

if((fpa = fopen(chfilein, "r")) == NULL)
| printf("unable to open file for channel upstream hydrograph......\n");
| J = 0;

while((fscanf(fpa, "%f%e\n", &time[J], &chhydro[J]) != EOF)
| ++J;
| fclose(fpa);

if((fpa = fopen(ofileout, "r")) == NULL)
| printf("unable to open file for combination hydrograph......\n");
| J = 0;
while((fscanf(fps, "%f%e\n", &time(J), &chydro(J))) != EOF)
    ++J;
fclose(fps);
if((fpcomb = fopen(ofileout, "w")) == NULL)
    printf("unable to open file for inlet combined hydrograph.....\n");
for(J = 0; J < NTIM; J++)
    ochydro[J] = ohydro[J] + chydro[J];
    fprintf(fpcomb, "%f%e\n", (J * DT)/60.0, ochydro[J]);
fclose(fpcomb);
return;
#include <stdio.h>
#include <mach.h>
#include <string.h>
#include kays/typea.h>
#include <3y3/atat.h>

/* Program to perform kinematic wave routing computations for
 * CHANNEL. The program uses the physical characteristics of
 * the drainage areas stored in a file that obtain its value from a spatial
 * database created with a geographic information system software called
 * ARC/INFO. Computations are done in English Units
 * */
/* Input to program are obtained from ARC/INFO database */

float chanrout();

void main()
{
  float DT, T;
  float LC, SC, JXC, SC, NC, WC;
  float Q0[400][400];
  float B[400][400], C[400][400], D[400][400], E[400][400];
  float THETA, ALPHA, M, UNITS;
  char shape[10], surface[5];
  int I, J, NTIM, NXO, NXC, count, inletnum, polynum;
  int preinletnum, arcnumber;
  FILE *fdata, *fps;

  /* In english units */
  UNITS = 1.486;

  printf("Enter total time for simulation in minutes \n");
  scanf("%f", &T);

  printf("Enter time increment in minutes\n");
  scanf("%f", &DT);
  T = T * 60.0;
  DT = DT * 60.0;
  NTIM = (T/DT);

  /* printf("Enter number of interval for DELTAX for overland\n");
 scanf("%d", &NXO); */

  printf("Enter number of interval for DELTAX channel\n");
  scanf("%d", &NXC);

  /* READ STORM DRAIN CHARACTERISTICS FROM A FILE THAT HOLDS INFORMATION
   * OBTAIN FROM THE SPATIAL DATABASE */
  fdata = fopen("northdrain.dat", "r");

  /* Parameter for overland and gutter or channel flow */
  count = 1;

  while((fscanf(fdata,"%d", &preinletnum)) == EOF)
  {
    fscanf(fdata,"%d%f%f%f%f%f%f", &inletnum, &arcnumber, &LC, &SC, &XC, &NC, &ZC, shape);
  }
chanrout (QO, NXO, LC, NXC, SC, NC, WC, ZC, T, DT, shape, count, preinletnum, inletnum) :

    count = count + 1;
} /* End of while loop */

    return;

} /* Function chanrout */

/* Program to perform kinematic wave routing computations for CHANNEL. */
The program uses the physical characteristics of the drainage areas and effective rainfall data stored in a spatial database created with a geographic information software called ARC/INFO. Computations are done in English Units.

/* Input to program are obtained from ARC/INFO database */
float chanrout(QO, NXO, LC, NXC, SC, NC, WC, ZC, T, DT, shape, count, preinletnum, inletnum)

float QO(400), (400);
float LC, ZC, SC, NC, WC, DT, T ;
char shape(10);
int count, NXO, NXC, preinletnum, inletnum;

float DC, DXC;
float TIME(400), AC(400)[400], QC(400)[400], AQO(400)[400];
float B(400)[400], C(400)[400], D(400)[400], E(400)[400];
float THETA, ALPHA, M, UNITS;

int I, J, NTIM;
char fileout(400), temp(20), filein(400), ctemp(20);
char nchfilein(400), nchtemp(20), nocfileout(400), nocampil(20);

struct stat bur;
FILE *fpc, *fupstr;

/* In English units */
UNITS = " 1.486;"

/* Input of channel flow parameters */
Enter channel length in feet
Enter channel distance increment in feet
Enter channel slope in ft/ft
Enter channel Roughness
Enter channel width or diameter in feet
Enter channel shape: RECT, CIRC, SQUARE, TRIANG, TRAP
Enter 'Z' for channel sideslope where Horiz:Vert is 3:1
('Z' is zero for shape RECT, CIRC, or SQUARE)

/* Input time parameters */
Enter total time for simulation, T
Enter time increment, DT

/* NTIM = (T/DT); */
/* Information to create a file with a different name for each polygon output */
strcpy(fileout, "nchrunoff");
sprintf(temp, "%d", preinletnum);
strcat(fileout, temp);
strcat(fileout, ".out");

printf("Count = %d", count, preinletnum);

/* Calculate ALPHA and M for various channel shapes */
if ((fpc = fopen(fileout, "w")) == NULL)
{
    printf("unable to open the output file ....\n");
    exit(1);
}

/* fprintf(fpc,"\nShape - %s\n", shape);*/
if (((strcmp(shape, "RECT")) == 0) || ((strcmp(shape, "rect")) == 0))
    /* If channel is circular the width is the diameter */
    DC = WC;
    ALPHA = (0.304 * sqrt((double)(SC)) / NC)
    * pow((double)(DC), (double)(1.0/6.0));
    M = 5.0 / 3.0;
else if (((strcmp(shape, "CIRC")) == 0) || ((strcmp(shape, "circ")) == 0))
    /* If channel is circular the width is the diameter */
    ALPHA = (0.304 * sqrt((double)(SC)) / NC)
    * pow((double)(DC), (double)(1.0/6.0));
    M = 5.0 / 4.0;
else if (((strcmp(shape, "SQUARE")) == 0) || ((strcmp(shape, "square")) == 0))
    /* If channel is circular the width is the diameter */
    ALPHA = (0.72 * sqrt((double)(SC)) / NC);
    M = 4.0 / 3.0;
else if (((strcmp(shape, "TRIANG")) == 0) || ((strcmp(shape, "triang")) == 0))
    ALPHA = (0.34 * sqrt((double)(SC)) / NC)
    * pow((double)(SC/(1.0 + pow((double)(ZC), (double)(2))), (double)(1.0/3.0));
    M = 4.0 / 3.0;
else if (((strcmp(shape, "TRAP")) == 0) || ((strcmp(shape, "trap")) == 0))
    /* for trapezoidal */
    else if (((strcmp(shape, "TRAP") == 0) || ((strcmp(shape, "trap") == 0))

/* Use standard form of Finite Difference equation */
/* NCX = (LC/DXC); */
DXC = (LC / (float)NCX);
printf("DXC = %f\n", DXC);

/* Write headings for channel flow output */
/* fprintf(fpc,"\n ALPHA = %4f M = %4f \n", ALPHA, M);*/
/* fprintf(fpc,"\n DISTANCE TIME AREA FLOW \n");*/

/* Open file of overland flow hydrograph and combine it with channel flow. */
strcpy(filein, "combhydro");
sprintf(ctimep, "%d", inletnum);
strcat(filein, ctemp);
strcat(filein, ".out");
strcpy(nchimp, "nchrunoff");
sprintf(nchtemp, "%d", inletnum);
strcat(nchimp, nchtemp);
strcat(nchimp, ".out");
strcpy(nchfilein, "nchrunoff");
strcpy(nchtemp, "%d", inletnum);
strcat(nchfilein, nchtemp);
strcat(nchfilein, ".out");
strcpy(nchfileout, "nchhydro");
sprintf(noctemp, "%d", inletnum);
strcat (nocfileout, noctemp);
strcat (nocfileout, " .out");

/* Or open channel file and continue routing */
if(count == 1)
|
  if((fupstr = fopen(filein, "r")) == NULL)
    printf("\nERROR - cannot open combined input hydrograph file....\n");
  else
    { J = 0;
      while((fscanf(fupstr, "%f%e\n", &TIME[J], &QC[0][J])) != EOF)
        { AC[0][J] = pow((double) (QC[0][J] / ALPHA), (double) (1.0 / M));
          ++J;
        }
      fclose(fupstr);
    }
else if (count > 1)
  { if (stat (filein, &buf) == 0)
      { combinlet(T, DT, inletnum);
        if((fupstr = fopen(nchfilein, "r")) == NULL)
          printf("\nERROR - cannot open combined inlet hydrograph file....\n");
        else
          { J = 0;
            while((fscanf(fupstr, "%f%e\n", &TIME[J], &QC[0][J])) != EOF)
              { TIME[J] = TIME[0] * 60.0;
                AC[0][J] = pow((double) (QC[0][J] / ALPHA), (double) (1.0 / M));
                ++J;
              }
            fclose(fupstr);
          }
        else
          { printf("\nERROR - cannot open combined input hydrograph file....\n");
            else
              { J = 0;
                while((fscanf(fupstr, "%f%e\n", &TIME[J], &QC[0][J])) != EOF)
                  { TIME[J] = TIME[0] * 60.0;
                    AC[0][J] = pow((double) (QC[0][J] / ALPHA), (double) (1.0 / M));
                    ++J;
                  }
                fclose(fupstr);
              }
          }
      }
  }
else
  { if((fupstr = fopen(filein, "r")) == NULL)
      printf("\nERROR - cannot open combined input hydrograph file....\n");
    else
      { J = 0;
        while((fscanf(fupstr, "%f%e\n", &TIME[J], &QC[0][J])) != EOF)
          { TIME[J] = TIME[0] * 60.0;
            AC[0][J] = pow((double) (QC[0][J] / ALPHA), (double) (1.0 / M));
            ++J;
          }
        fclose(fupstr);
      }
  }
*/
Begin Time Loop

/*
 * J = 0;
 * if (J == 0)
 * fprintf(fpc, "%f\t%e\n", (J)*DT/60.0, QC[0][J]);
 */

for(J = 1; J <= NTIM ; J++) { /* Boundary condition at x = 0.0 for every Time Step */

/* Read in hydrograph from upstream channel or Combined hydrograph for
overland and channel flow. */

/* If no direct overland flow into the channel */
QO[NXO][J] = 0.0;

/* Begin distance loop */
for(I = 1; I <= NXC ; I++) { /* Standard Form */

AQO[NXO][J] = (AQO[NXO][J] + QO[NXO][J-1]) / 2.0;
B[I][J] = AQO[NXO][J] * DT + AC[I][J-1];
C[I][J] = (AC[I][J-1] + AC[I-1][J-1]) / 2.0;
D[I][J] = AC[I][J-1] - AC[I-1][J-1];
AC[I][J] = B[I][J] - ALPHA * M * (DT/DXC) - pow((double)(C[I][J]),(double)(M - 1.0)) * D[I][J];
if (AC[I][J] < 0.0)
AC[I][J] = 0.0;
QC[I][J] = ALPHA * pow((double) AC[I][J],(double) M);

/* Check for numerical stability with stability factor theta, and if
* theta is less than unity is ok to use standard form*/
if (AQO[NXO][J] == 0)
THETA = ALPHA * M * pow((double) AC[I-1][J-1], (double)(M - 1.0)) * (DT/DXC);
else
THETA = (ALPHA / (AQO[NXO][J] * DXC)) * pow((double) (AQO[NXO][J] * DT + AC[I-1][J-1]),(double) (M)) - pow((double) (AC[I-1][J-1]),(double) (M));

/* If theta is greater than unity, use the Conservation form of the
* finite difference approximation */
if (THETA > 1.0) {
QC[I][J] = AC[I][J] = pow((double)(QC[I][J] / ALPHA), (double)(1.0 / M));
if (fabs(I*DWC - LC) < 0.0091)) {
/*fprintf(fpc,"%f\t%e\n", (I)*DWC, (J)*DT, AC[I][J], QC[I][J]);*/
fprintf(fpc, "%f\t%e\n", (J)*DT/60.0, QC[I][J]);
}
}

/*End of Distance loop */

/*End of Time loop*/
fclose(fpc);
return;"
/ Function combinlet */
/* Program to combined hydrographs at a common inlet. */
combinlet(T, DT, inletnum)
int inletnum;
float DT, T;

float time[400];
float ohydro[400], chydro[400], ochydro[400];

int I, J, NTIM;
char filein[400], ctemp[20], chfilein[400], chtemp[20];
char ocfileout[400], octemp[20];

FILE *fpn, *fps, *fpcomb;

T = T * 60.0;
DT = DT * 60.0;
NTIM = (T/DT);

// Initialize the array fhydro to */
for(J = 0; J < 400; J++)
{
ohydro[J] = 0.0;
}

/* Combine hydrograph for overland flow and channel upstream flow at inlet */
strncpy(filein, "combhydro");
sprintf(ctemp, "id", inletnum);
strcat(filein, ctemp);
strcat(filein, ".out");

strncpy(chfilein, "nchrunoff");
sprintf(chtemp, "id", inletnum);
strcat(chfilein, chtemp);
strcat(chfilein, ".out");

strncpy(ocfileout, "nochydro");
sprintf(octemp, "id", inletnum);
strcat(ocfileout, octemp);
strcat(ocfileout, ".out");

if((fpn = fopen(filein, "r")) == NULL)
{
    printf("unable to open file for overland flow hydrograph.....\n");
    J = 0;
    while((fscanf(fpn, "%f%e\n", stime[J], shoydro[J]) != EOF)
    {
        ++J;
    }
    fclose(fpn);
}

if((fps = fopen(chfilein, "r")) == NULL)

printf("unable to open file for channel upstream hydrograph.....\n");

J = 0;

while((fscanf(fps, "%f%e\n", &time[J], &chydro[J]) != EOF))
{
    ++J;
}
fclose(fps);

if((fpcomb = fopen(ofileout, "w")) == NULL)
{
    printf("unable to open file for inlet combined hydrograph.....\n");
}

for(J = 0; J <= NTIM; J++)
{
    ochydro[J] = chydro[J] + chydro[J];
    fprintf(fpcomb, "%f%e\n", (J * DT) / 60.0, ochydro[J]);
}
fclose(fpcomb);
return;
#include <stdio.h>
#include <math.h>
#include <string.h>

/* Program to combined hydrographs at a common inlet. */

void main ()
{
    float DT, T, time[400];
    float nhydro[400], shydro[400], fhydro[400];
    int I, J, NTIM;

    FILE *fpn, *fps, *fpcomb;

    printf("Enter total time for simulation in minutes \n");
    scanf("%f", &T);
    printf("Enter time increment in minutes\n");
    scanf("%f", &DT);
    T = T * 60.0;
    DT = DT * 60.0;
    NTIM = (T/DT);

    /*Initialize the array shydro to */
    for(J = 0; J < 400; J++)
    {
        shydro[J] = 0.0;
    }

    if((fpn = fopen("nhydrograph", "r")) == NULL)
    {
        printf("unable to open file for north hydrograph....\n");
        J = 0;
    }
    while((fscanf(fpn,"%f%e\n", &time[J], &nhydro[J])) != EOF)
    {
        ++J;
    }
    fclose(fpn);

    if((fps = fopen("shydrograph", "r")) == NULL)
    {
        printf("unable to open file for south hydrograph....\n");
        J = 0;
    }
    while((fscanf(fps,"%f%e\n", &time[J], &shydro[J])) != EOF)
    {
        ++J;
    }
    fclose(fps);

    if((fpcomb = fopen("hydrograph", "w")) == NULL)
    {
        printf("unable to open file for final hydrograph....\n");
    }
for (J = 0; J < NTIM; J++)
{
    fhydro[J] = nhydro[J] + shydro[J];
    fprintf(fpcomb, "%f\t%f\n", (J * DT)/60.0, fhydro[J]);
}
fclose(fpcomb);
return;
}
```c
#include <stdio.h>
#include <math.h>
#include <string.h>
/* Program to combine hydrographs at a common inlet. */

void main()
{
    float DT, T, time[400];
    float nhydro[400], shydro[400], fhydro[400];
    int I, J, NTIM;
    FILE *fpn, *fps, *fpcomb;

    printf("Enter total time for simulation in minutes \n");
    scanf("%f", &T);
    printf("Enter time increment in minutes\n");
    scanf("%f", &DT);
    T = T * 60.0;
    DT = DT * 60.0;
    NTIM = (T/DT);

    /* Initialize the array fhydro to */
    for(J = 0; J < 400; J++)
    {
        fhydro(J] = 0.0;
    }

    if((fpn = fopen("hydrograph", "r")) == NULL)
    {
        printf("unable to open file for hydrograph at final inlet......\n");
    }
    J = 0;
    while((fscanf(fpn, "%f%e\n", &time(J], &nhydro(J])) != EOF)
    {
        ++J;
    }
    fclose(fpn);

    if((fps = fopen("comhydro18.out", "r")) == NULL)
    {
        printf("unable to open file for overland flow hydrograph at final inlet\n");
    }
    J = 0;
    while((fscanf(fps, "%f\n", &time(J], &shydro(J])) != EOF)
    {
        ++J;
    }
    fclose(fps);

    if((fpcomb = fopen("finhydrograph", "w")) == NULL)
    {
        printf("unable to open file for final hydrograph......\n");
    }
}```
for(J = 0; J < NTIM; J++)
{
  fhydro[J] = nhydro[J] + shydro[J];
  fprintf(fpcomb, "%f\t%g\n", (J * DT)/60.0, fhydro[J]);
}
fclose(fpcomb);
return;
}
VITA

Richard Gilbert Greene was born on May 26, 1959 in Catherineville, Mahaicony, East Coast Demerara, Guyana. He attended high school at Mahaicony Government Secondary School and later proceeded to the Government Technical Institute in Georgetown, Guyana, where he graduated with a Diploma in Land Surveying in 1978. In 1978, he began working as a technician with the Lands and Surveys Department of the Guyana Ministry of Agriculture and later became a Sworn Land Surveyor with the department. In 1982, he began his studies at The Ohio State University where he received his B. S. in Surveying on March 22, 1985, and his M. S. in Civil Engineering on September 3, 1987. He later attended Louisiana State University and currently is a candidate for the Doctor of Philosophy in the Department of Civil Engineering. He is married to the former Meredith Muizenberg, and together they have two daughters, Giselle and Kristen.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Richard Gilbert Greene

Major Field: Civil Engineering

Title of Dissertation: Hydrologic Modelling With a Spatial Database

Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

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Date of Examination:

September 18, 1993