A PROCESS FOR INTERFACING A HYDROLOGIC MODEL TO A GEOGRAPHIC INFORMATION SYSTEM

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CHAPTER I

INTRODUCTION

General

The recent heightened awareness of environmental issues has caused the development of new technologies which are needed for dealing with problems that pose a potential or real hazard to the environment. These new technologies and methods are necessary because current environmental problems are typically complex in nature and require considerable expertise to understand. Although hydrologic models are not new, they have emerged as the most logical and efficient means for addressing the majority of environmental problems related to water quality.

Hydrologic models have been used for years to address problems related to storm water management and flood control. More recently, hydrologic models have been modified to address soil erosion, water quality and contaminant transport issues. The complexity of natural processes related to water quality results in the need for hydrologic models to have a large number of parameters to adequately characterize the processes.

Collecting enough data to accurately represent some parameter values can be difficult. Most parameters used in hydrologic models are determined from spatially variable data that is unique to the watershed being studied. Due to the high variability, the data base for a single watershed can be quite large and require extensive effort to assemble. The majority of this effort consists of collecting enough data to accurately determine the parameter values. Data collection might include many hours extracting data from such sources as United States Department of Agriculture, Soil Conservation Service (USDA-SCS), soil surveys and land use maps or United States Geological Survey (USGS) topographical maps. The need to alleviate some of the labor involved with organizing and manipulating large data bases has given rise to powerful data managers available in software packages that store spatial geographic data. Such packages as Geographical Information Systems (GIS's) have the ability to assemble watershed data more conveniently and efficiently than traditional methods used by hydrologic modelers.

GIS provides a vehicle for data base assembly that offers a quick and efficient method for determining parameters for hydrologic models. GIS can store, manipulate, analyze, and display spatially distributed data. GIS's have emerged as the major tool for solving complex natural resource problems that require extensive geographical data (Nystrom et al., 1986). Also, GIS's have been shown to decrease the work necessary to complete a data base for a watershed (Stuebe and Johnston, 1990). The advantage that GIS offers is that it reduces the tedious manual work involved with collecting data for parameter estimation.

Statement of Problem

It is evident that GIS can be used in a manner that eliminates a significant amount of work required to collect the necessary data for parameter evaluation. Also, the use of hydrologic models will be extensive in solving water related environmental problems. Since GIS can manipulate and store the types of data used by hydrologic models, it is apparent that the benefits in using hydrologic models in conjunction with GIS are appreciable. The obvious compatibility of GIS and hydrologic models has sparked the need to link these programs together through interface programs. Interface programs provide a connection that can transfer data automatically from GIS to a hydrologic model and back. In addition, the interface can serve as a guide to the user navigating between GIS and a hydrologic model.

An interface program may enable a user with limited experience in hydrology to use data stored in a GIS for estimating parameter values required by a hydrologic model. Without the use of an interface, a user with little or no knowledge of hydrologic processes may find it difficult to use data stored in GIS for estimating parameters. Also, accessing data stored in a GIS without the use of an interface may result in the adoption of a less data intensive effort resulting in a more approximate hydrologic model. A high level of knowledge of both hydrologic processes and GIS is needed to access the proper data in a GIS and use it to estimate parameters. To reduce the user knowledge requirements, an automated process that links a GIS with hydrologic models is needed.

The automatic process linking GIS with a hydrologic model needs to minimize user interaction with any data, calculations or processes. An optimum procedure would be for the user to ask for a certain parameter which would be automatically entered into a hydrologic model's input file. This type of procedure would assist the user in accessing data stored in GIS and estimating parameters required by a hydrologic model. No system, however, should completely override the judgement of the user. Ultimately, the user of the system must accept the responsibility for system output.

Objectives

There are two objectives in this project. The first objective is to develop an interface program that accesses data stored in a watershed data base and then uses that data to calculate some of the parameters required by a hydrologic model. These parameters will be automatically entered into the model's input file with minimal user interaction. The second objective is to use the interface system to study how different numbers of sub-basins impact the runoff hydrograph for a particular watershed.

Procedure

The first step was to develop a data base for the Cow Creek watershed located north of Highway 51 near Stillwater, Oklahoma. Much of the data for the watershed data base was collected and organized using a GIS named GRASS (Geographical Resources Analysis Support System) (Corps of Engineers, 1988). To access the watershed data stored in GRASS, the watershed boundary was digitized and defined within the GRASS system. Soil types and land uses for the Cow Creek watershed were determined from an existing data base within GRASS, and then added to the watershed data base. Other files relating information about the watershed were manually added to complete the watershed data base.

The second step was to design an interface program that could provide an automated process for entering parameter values into a hydrologic model's input file. This step was necessary in achieving the first objective of the project. For this project, the interface program was formatted to enter parameter values into an input file designated for the hydrologic model, HEC-1 (Corps of Engineers, 1990). The interface program was designed to read files from the watershed data base and use that data to determine three parameters: weighted curve number, lag time, and basin area. The interface then automatically entered these parameters into the HEC-1 input file. An illustration describing the processes used by the interface program to read the data

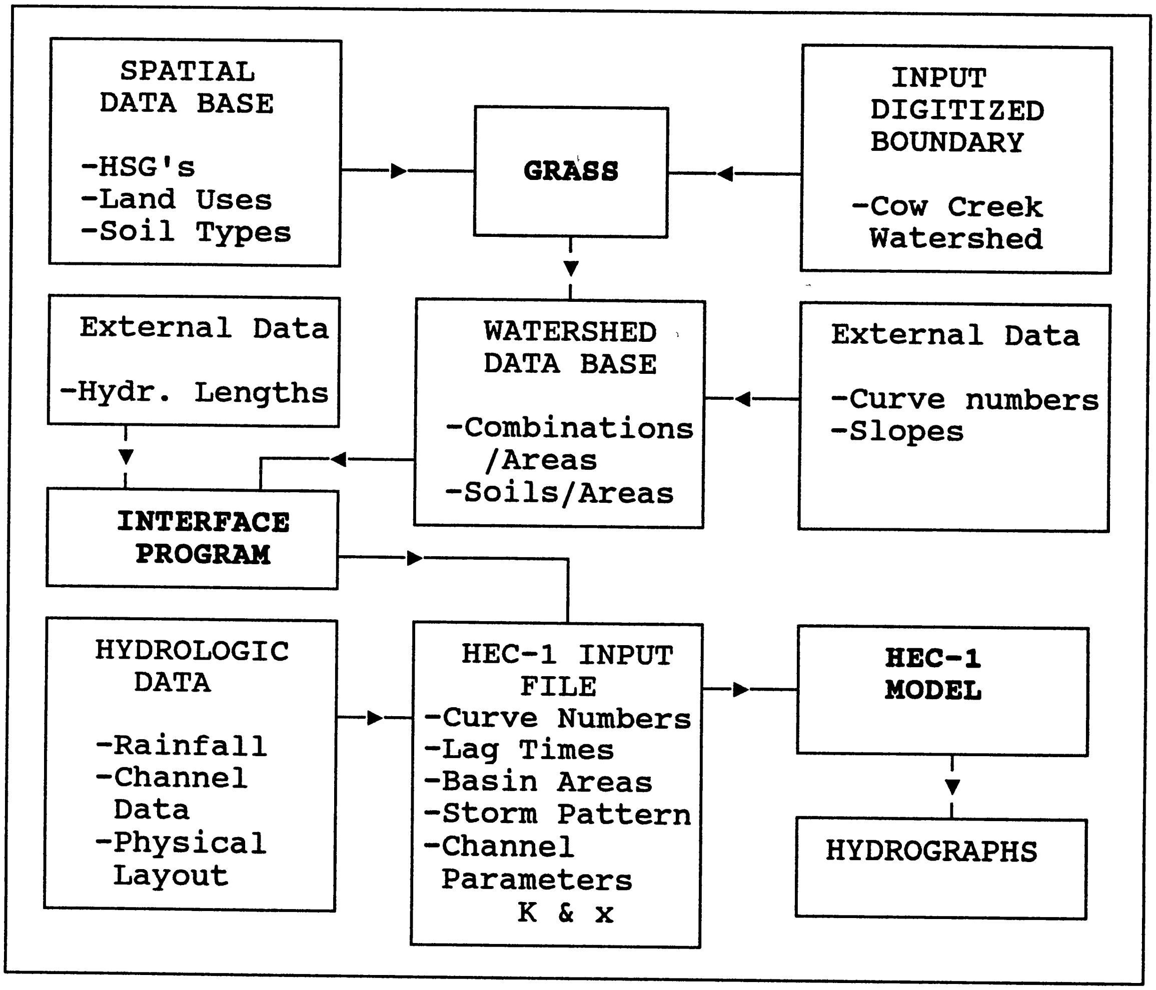

Figure 1. Relationships between GRASS, Interface Program, and HEC-1

base files and write to the HEC-1 input file is shown in Figure 1.

The third step was to create a HEC-1 input file which represented the Cow Creek watershed. This step also included the estimation of additional parameters that were outside of the interface's capability. These additional parameter values were necessary for describing rainfall pattern and channel routing. Consequently, they were determined from sources other than GRASS and manually entered into the input file. After all the parameter values were entered into the input file, the HEC-1 model was used to accomplish the second objective.

The final step was to compare the runoff hydrographs produced from HEC-1 to determine how the watershed reacted under different conditions. Three HEC-1 input files were created, each representing the Cow Creek watershed divided into a different number of sub-basins. The numbers of sub-basins used in the analysis were one, three, and six sub-basins. A hydrograph at the outlet of the Cow Creek watershed was determined using HEC-1 for each number of sub-basins. The three different hydrographs each corresponding to a different number of sub-basins were then compared.

CHAPTER II

LITERATURE REVIEW

Introduction

Before an interface program can be designed, a general understanding of how GIS's and hydrologic models operate is required. For this project in particular, a thorough understanding of HEC-1 and GRASS was critical in developing an interface program that linked the two together. To better understand GRASS and HEC-1, a review of the basic concepts common to most GIS's and hydrologic models is provided within the Literature Review.

Geographical Information Systems

A basic definition of GIS is a data manager that can analyze, store, and display both spatial and non-spatial data. Most GIS's have the following characteristics: a method for entering data into the data base, systems for displaying and sorting the data, and an ability to perform calculations with the data (Jett et al., 1979). The term GIS is a generic term. Currently, there are many brands of GIS's on the market. Two of the more popular GIS's used in conjunction with hydrologic models are GRASS and ARC/INFO (Environmental Systems Research Institute, 1989). Although these two GIS's may be used for the same purpose, they use different methods for storing their spatial data.

The first step in understanding GIS is to understand how spatial data is stored. GIS's are divided into two categories based on their methods for storing spatial data. GIS's either store their spatial data in vector form (ARC/INFO) or in raster form (GRASS).

Vector Data Base

A vector data base employs points, lines, and polygons to store spatial data. Points define a line which, in turn, define a polygon. Two points are required to create a line and a minimum of three lines are required to create a polygon. Lines attempt to represent the boundaries of the actual spatial data. The resolution of vector based data maps is dependent upon the length of the lines within the polygons. As shown in Figure 2, the shorter the lines, the more accurately they represent an actual data boundary. As a general rule, vector data tends to be more accurate than raster data (Jett et al., 1979).

Raster Data Base

A raster data base is a system that represents spatially variable data in grid cells. Each grid cell is assigned a location using an (X,Y) coordinate system. Different attributes based on data within the data base are assigned to each cell. For example, if grid cell (20,10)

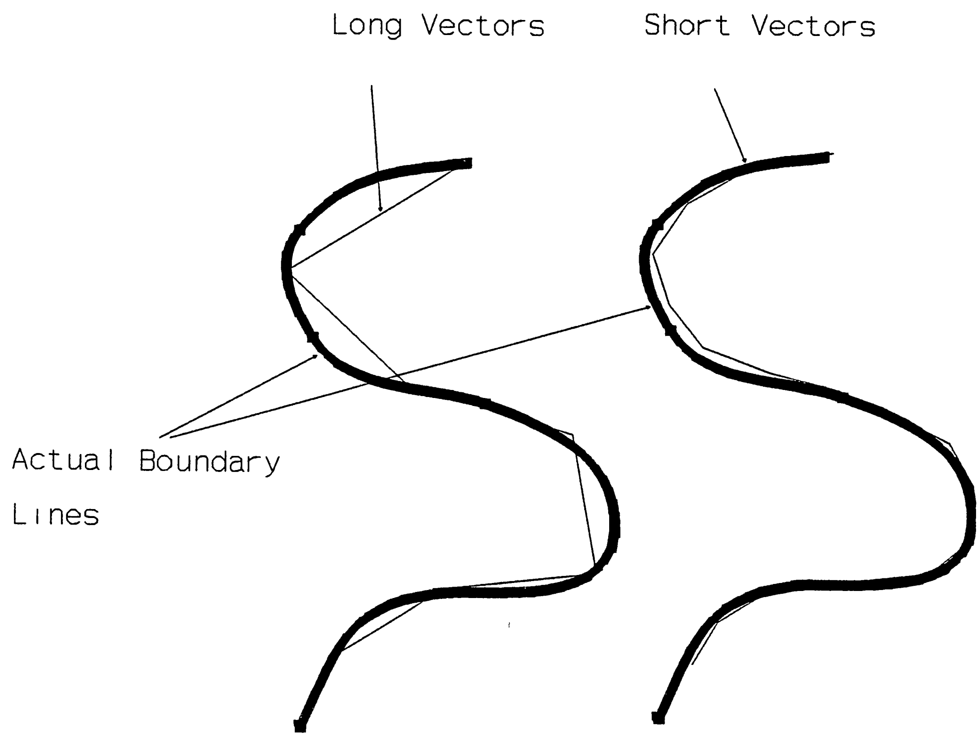

Figure 2 The Effects that Vector Lengths have on Describing Boundary lines

lies over Soil A, an attribute of Soil A will be assigned to that grid cell. If a group of cells share a common attribute and are adjacent to each other, they are referred to as a polygon as shown in Figure 3.

The resolution of raster cells may be changed by adjusting the area of each cell. Obviously, the smaller the cells, the more accurate the data base represents the original data boundaries. However, the smaller the cells, the higher the computational effort. Once the vector and raster data bases are understood, the general functions used by GIS's to manipulate and organize data can be discussed.

Layers

GIS's unique overlaying capability is one of its most powerful functions. GIS has the ability to overlay two sets of data to create a third set. This operation can be performed through the use of "layers". A data layer stores spatial information for a single type of data either in raster or vector form. Each type of data has its own layer. If two layers representing the locations of two types of data are overlaid, the location of a third type of data can be derived. For example, if a soil data layer is laid onto a land use data layer, a soil by land use data layer is produced. More specifically, the polygons on the soil layer intersect with the polygons on the land use layer to create new polygons. Each new polygon can then be assigned a new attribute related to the two types of data. This process

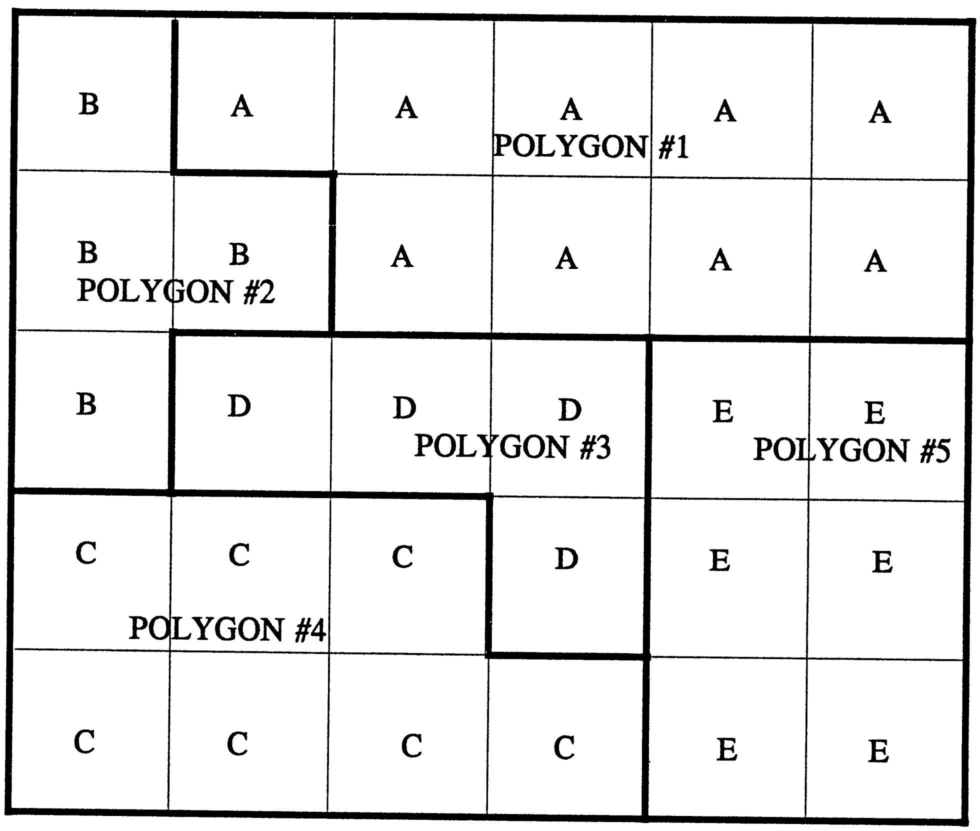

Figure 3. Polygons Defined within a Raster Data Base

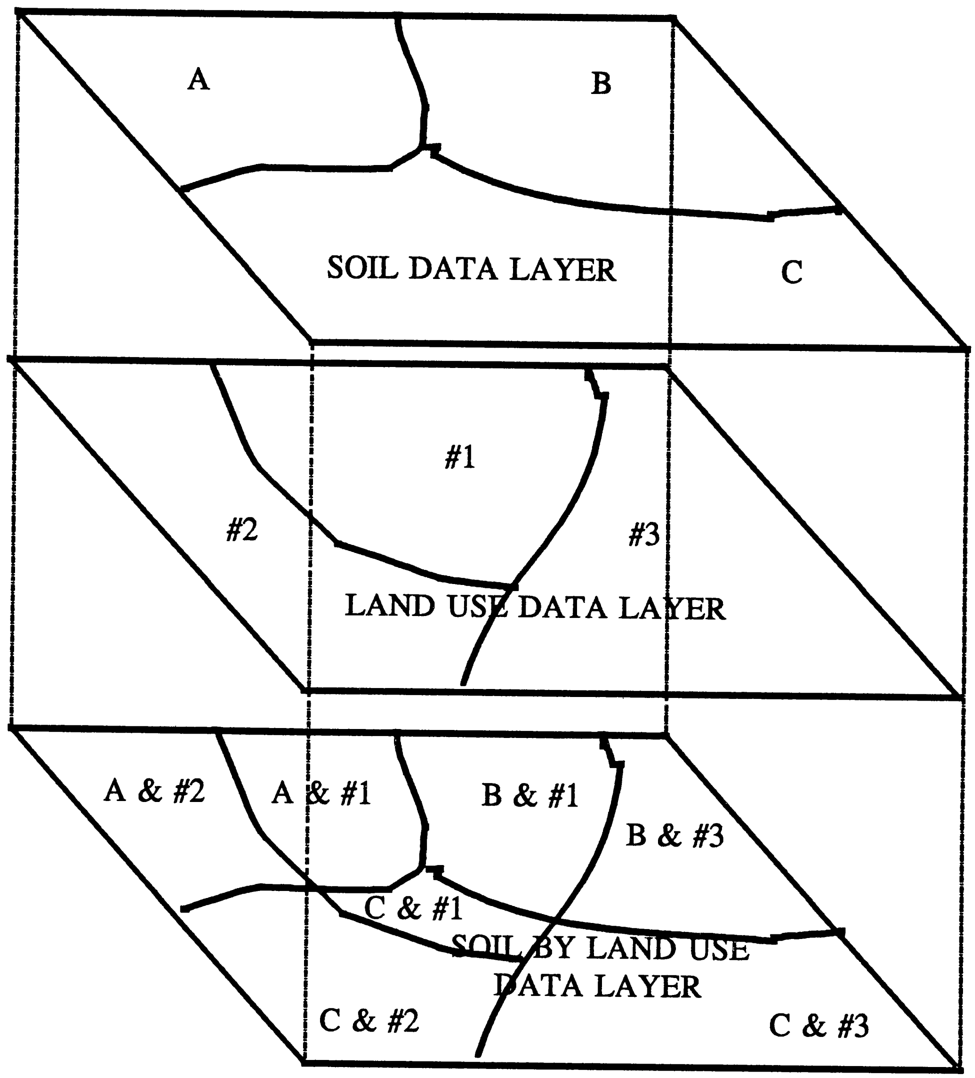

Figure 4 A Process for Creating New Data Layers

is illustrated in Figure 4.

Hydrologic Models

Hydrologic models simulate flow and storage processes resulting from a hydrologic event. Some hydrologic models simulate surface runoff while others simulate water movement through the soil matrix. All models use parameters unique to the watershed or area of study to describe how water movement occurs. Usually, as a process increases in complexity, more parameters are required by the model to simulate that process. An important characteristic of hydrologic models is how they represent parameters. Models can be classified as either distributed or lumped.

Distributed Models

A distributed model simulates processes at discrete locations using either cells or points. Each discrete location represents an area with attributes based on parameters unique to that location. More generally, a completely distributed model describes the processes at a point and then integrates over three dimensional space and time to produce the total watershed response (Haan et al., 1991). Because it is impossible to describe the processes at each and every point, distributed models typically define averaged parameters for a region or segment. Because distributed models contain parameters which are averaged, a certain degree of data lumping occurs. Therefore, there is no such thing as a perfectly distributed model.

Lumped Models

Completely lumped models display no distributed properties at all. To describe a process, lumped models use parameters that represent an averaged value for a given watershed or area. For example, if the infiltration rate was a parameter of concern, a lumped model would use an average infiltration rate value for an entire watershed. HEC-1 is an example of a lumped hydrologic model.

HEC-1

HEC-1 is a hydrologic model developed at the Hydrologic Engineering Center (HEC) in Davis, California, by the U.S. Army Corps of Engineers. The model's purpose is to simulate surface runoff from a watershed due to a hydrologic event. HEC-1 views the watershed as a network of interconnected hydraulic components. Hydraulic components are defined as sub-basins, stream channels or reservoirs. The model was developed under the premise that processes simulated by the model could be based on parameters that reflect average conditions within the hydraulic components (Corps of Engineers, 1990). Because average conditions are used to represent parameters in the sub-basins, the model operates as a lumped model.

For each sub-basin, the model requires a different set of parameter values. The parameters used are dependent upon the methods used to model the hydrologic processes. HEC-1 offers several methods for determining each process. For example, to determine the infiltration loss rate, HEC-1 offers six methods including the Holton method (Holton et al., 1975), SCS Curve Number method (Soil Conservation Service, 1972), and the Green and Ampt method (Mein and Larson, 1973). Each method has its own set of parameters some of which may overlap. Hence, the parameters that are required by HEC-1 are dependent upon the methods chosen by the user. Determining which methods to be used by the model in order to describe the processes is a prerequisite to designing an interface program.

Interfacing Methods

There have been several studies that used GIS technology to assist in entering parameters into hydrologic models. However, before any attempt is made to link a GIS to a model, a study is usually conducted to determine whether or not the GIS has the capability to benefit the model. In these types of initial investigations, the user acts in place of an interface program. The user manually accesses data within GIS, calculates the parameters, and enters them into the model's input file.

Stuebe and Johnston (1990) studied the possibilities of using GIS rather than soil surveys and maps for collecting data. They used two methods for entering the parameters into a model. The only difference between the two methods was that they obtained their data from different sources. The first method extracted data from maps and soil surveys while the second method accessed data from GRASS data files. In both methods, they manually calculated the parameters and entered them into the models input files. For this particular case, the users were acting as an interface between GRASS and the hydrologic model. The results of the comparison showed that the GIS was an acceptable means of reducing parameter input effort for the hydrologic models.

Once it is proven that a GIS can benefit a hydrologic model, methods are developed that automatically transfer data from GIS to the model. The most common method of harnessing the power of GIS has been through the use of interface programs. Because each model and GIS operates a little differently, a different interface program is necessary to link each model with each GIS. Although the algorithms of interface programs may be similar, currently universal interfaces do not exist.

Wolfe and Neal (1988) used GRASS to decrease the parameter input effort for the hydrologic model FESHM (Finite Element Storm Hydrograph Model) (Ross et al., 1979). FESHM is a distributed parameter model that uses the Mein-Larson version of the Green-Ampt equations (Mein and Larson, 1973) to calculate rainfall runoff. They used algorithms developed as modules within the UNIX operating system to determine parameter values required by the model. The modules were accessed through the GRASS framework. The user then manually copied the parameters from the GRASS output files and placed them into the FESHM input files. Again, the user was acting as the link between GRASS and FESHM. An interface program used to automatically transfer the parameters from GRASS to FESHM was not yet designed. Hession (1988) and Shanholtz and Zhang (1989), in separate projects, also used GIS technology to assist in entering parameters into FESHM.

Another model that has been successfully linked to GRASS is the hydrologic model, MULTSED (MULTiple Watershed SEDiment Routing) (Simons et al., 1981; Hodge et al., 1986). Hodge et al. (1988) linked a version of MULTSED, ARMSED, with GRASS to decrease model parameter input effort. ARMSED is the Army's version of the model MULTSED. ARMSED is a distributed physical process model that uses the Green-Ampt equations for determining infiltration losses. The model can estimate total runoff volume for both sub-basins and entire watersheds in addition to runoff hydrographs and total sediment yield. An interface was used to link GRASS and ARMSED together. The interface was a program that guided the user between ARMSED and GRASS to develop GRASS output files, perform calculations, and create ARMSED input files.

Vieux and Kang (1990) proposed a system, Waterworks, to model peak discharges based on hydrological events. The

Waterworks package also included GRASS in addition to several C programmed subroutines which operate under UNIX. Waterworks operates under two phases. In the first phase, Waterworks uses GRASS to generate a slope and aspect map, select a watershed outlet, evaluate data, and prepare input data required for the model parameters. The second phase of Waterworks includes the hydrologic modeling. In this phase, Waterworks computes parameters for the model, and then models the hydrologic event. Modeling is performed using the C programmed routines especially adapted for the Waterworks package.

Hession (1990) used ARC/INFO to assist in entering parameters into the AGNPS (Agricultural Nonpoint Source) model (Young et al., 1987). AGNPS is a distributed model which uses grid cells as its discrete intervals. Each of the cells requires 21 parameters. An area weighted average value for each parameter is calculated for each grid cell. For example, if a grid cell contains more than one curve number, ARC/INFO calculates the area averaged curve number for the whole cell. The resulting file contains area weighted values for each grid cell. Parameters for each grid cell are then defined and organized into the AGNPS input file format. This process is performed within ARC/INFO. After the input file has been built, it is manually exported into the PC based AGNPS model.

ARC/INFO has also been linked to chemical transport models. Zhang et al. (1990) interfaced ARC/INFO with the

CMLS (Chemical Movement in Layered Soils) model (Nofziger and Hornsby, 1986). The data required for the parameters were extracted from a raster based data set and then converted into a vector data base for use in ARC/INFO. The programming language, SML, within ARC/INFO was used to drive the interface and perform the necessary steps to create an input file for the model. Results produced by the CMLS model were then exported by the interface to ARC/INFO for presentation.

Other examples of GIS technology in conjunction with chemical transport models are discussed by Heatwole (1990) and Davis and Heatwole (1990). Both papers discuss the application of GIS to the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model (Davis et al. 1990). They developed a program, KBS, that acted as an interface between the GIS and GLEAMS. KBS retrieved data from data files and performed the necessary calculations to obtain parameters required by GLEAMS. In this particular case, no operations were performed within the GIS. The KBS program merely transferred and interpreted data between GLEAMS and data files produced by the GIS. In addition to reducing the parameter input effort for GLEAMS, KBS reduced the user expertise requirements. In other words, users with minimal knowledge of the GLEAMS parameters could obtain accurate results when using the model.

There have been several projects that have linked HEC-1 to a GIS. Huff (1989) and Thirkill (1986), reviewed projects that linked HEC-1 with two different GIS's. Both of the GIS's that were linked to HEC-1 used vector data bases. Also, both interfaces used the same algorithms and manufactured similar parameters. In both cases, the SCS curve number method was used to determine runoff volumes. All parameters were automatically entered into a HEC-1 input file.

Cline et·al. (1989) developed a method of reducing parameter input effort for HEC-1 using a three phase process. The first phase used Auto-CAD to extract, organize, and display watershed data. Phase one defined watershed boundaries, elevations, and channels which led to the determination of areas, slopes, and lengths. Phase two of the process used a program to calculate HEC-1 parameters, such as the curve number and Mannings coefficient, for each sub-watershed. Phase three combined a skeleton HEC-1 input file with the parameters determined in phase two.

Interfaces have been also developed for models and GIS's that are not as widely used. Holbert (1990) developed a hydrologic model, HYDROPAC, that used data from a GIS for stormwater management planning. The model was distributed and accessed raster data within the GIS which was then entered into each discrete interval to determine direction and amount of flow for each cell. Data accessed from the GIS was elevation, land use, and soil. From this, runoff from each cell was determined for each time step.

Muzik (1988) developed an interface program that linked a raster based GIS to a hydrologic model. Data stored in the GIS included land cover classification, soil drainage classifications, runoff curve numbers, rainfall statistics, and elevation data. The model used the SCS curve number method for calculating runoff. To determine lag time, the GIS computed the basin area, hydraulic length, and mean slope. Furthermore, the GIS assigned a curve number for each grid cell and then calculated the weighted curve number for the given watershed. The interface then exported the parameters from the GIS to the model.

In a recent effort to integrate GIS technology with hydrologic, hydraulic, erosion, and sediment transport models, Oslin et al. (1988) developed the interface program, STREAMS (Soil, Transport, Rainfall, Erosion, and Mapping System). STREAMS purpose was to transfer data from a raster GIS to a model. STREAMS accessed the data within the GIS necessary for determining parameters required by the Universal Soil Loss Equation (Wischmeier, 1976).

Another example of a GIS application was discussed by Hill et al., (1987). They applied a GIS to the WAHS (Watershed Hydrology Simulation) model (Singh, 1983). A GIS developed especially for the WAHS model was used to create the date base. The interface program accessed data within the GIS, calculated an area weighted curve number, and entered it into the model.

Variable Sub-basins

Interface programs can offer the luxury of performing tests with minimal user effort that, in the past, may have required extensive effort. This research addresses the effects that the number of sub-basins has on a watershed's hydrograph. To determine the effects, the number of sub-basins for a given watershed is varied. Then the hydrographs representing the watershed as *n* number of sub-basins are compared. Without an interface program, production of the hydrographs would require considerable effort.

Boyd et al., (1979) varied the number of sub-basins in a 30,000 acre watershed to determine the effects on the runoff hydrograph. This process was carried out without the assistance of a GIS. The number of sub-basins were varied from 1 to 15. It was found that the peak flows and lag times were fairly stable for all numbers of sub-basins. They determined that it was more important to represent the physical arrangement of the sub-basins accurately in the input files than to consider the number of sub-basins.

Summary

There have been many attempts to link GIS's and models together. Although there have been many interface programs, the one goal that all the applications share is to use GIS as a method for reducing the effort required when determining parameter values for a model. If an interface can accomplish this task, it is a success. A GIS can then be applied to aid in the research of hydrological processes.

CHAPTER III

DEVELOPING THE WATERSHED DATABASE

Introduction

The intent of a watershed data base is to provide the interface program with enough information to determine certain parameter values. The data base is a group of files containing watershed data arranged in a specific format. Data files that make up the watershed data base can be created by a GIS or other methods. Although the intent of this project was not to study the rainfall-runoff processes of any particular watershed, the procedure for developing a watershed data base began by choosing a specific watershed to provide actual geographic data.

Watershed

Cow Creek watershed north of Highway 51 was chosen to provide the geographic data for this project. Cow Creek watershed is located in Payne County approximately 4 miles northwest of Stillwater, Oklahoma, and encompasses approximately 13 square miles (8000 acres). The watershed is situated in a rural setting containing farm land, pasture land, and wooded areas. The topography is typically flat with some rolling hills. Figure 5 depicts the Cow Creek watershed boundary and its major drainage channels and Figure 6 defines the locations of the six sub-basins within the watershed. Figure 7 shows the watershed divided into three sub-basins which is the result of a combining process based on the locations of the six sub-basins in Figure 6.

Two assumptions were made to simplify the watershed's characteristics. These assumptions were made to reduce the number of parameters required by HEC-1 necessary for modeling the hydrologic processes of the watershed. The assumptions were justified because the true hydrologic processes of the Cow Creek watershed were not a major concern for this project.

The first assumption was that there were no impervious areas on the watershed, such as large parking lots. Since the Cow Creek watershed was mostly undeveloped, the total impervious area was considered to be negligible. Therefore, the impervious area was automatically entered into the HEC-1 input file as zero. HEC-1 requires the percent of impervious area when using the curve number method for calculating runoff (Corps of Engineers, 1990).

The second assumption was to ignore the ponds on the watershed. Through the years, many small ponds have been constructed within the watershed to supply cattle with water and to control soil erosion. To take into consideration the effects of these ponds, reservoir routing would have to be performed on each pond which would be a tedious and cumbersome process. These small ponds would have little

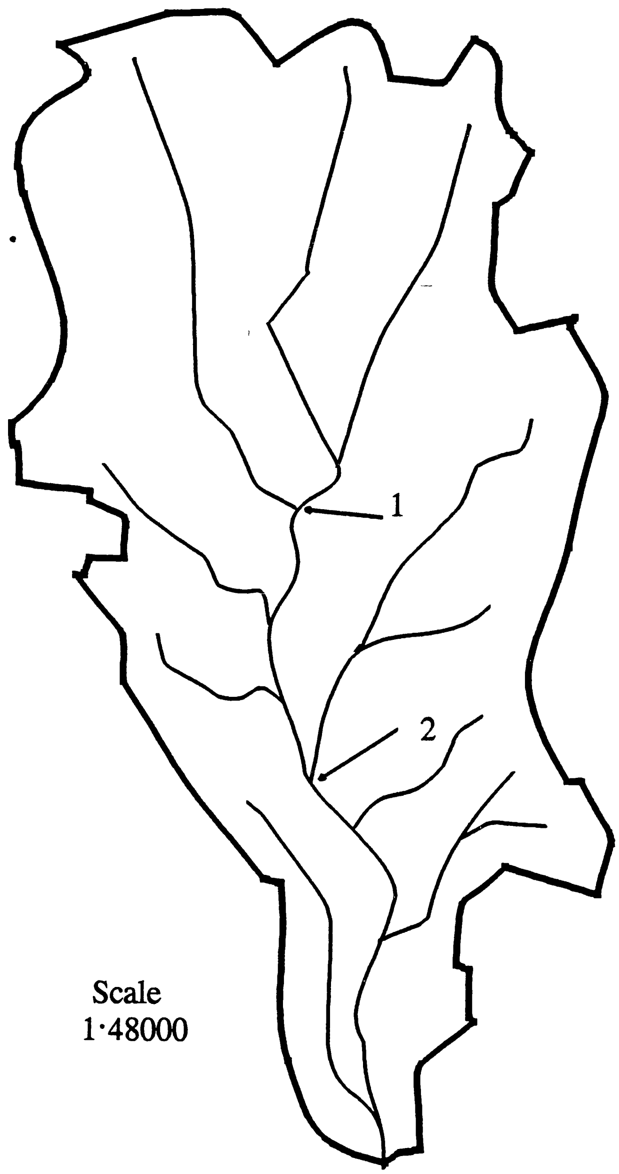

Figure 5 The Cow Creek Watershed and Major River Channels

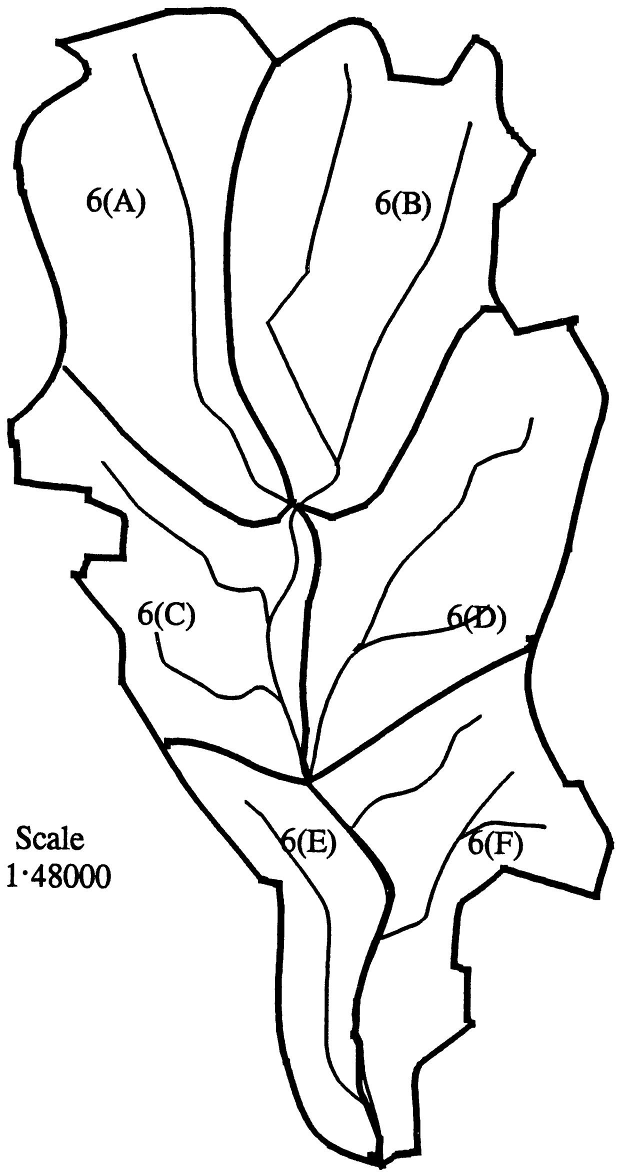

Figure 6 The Cow Creek Watershed Divided into Six Sub-basins

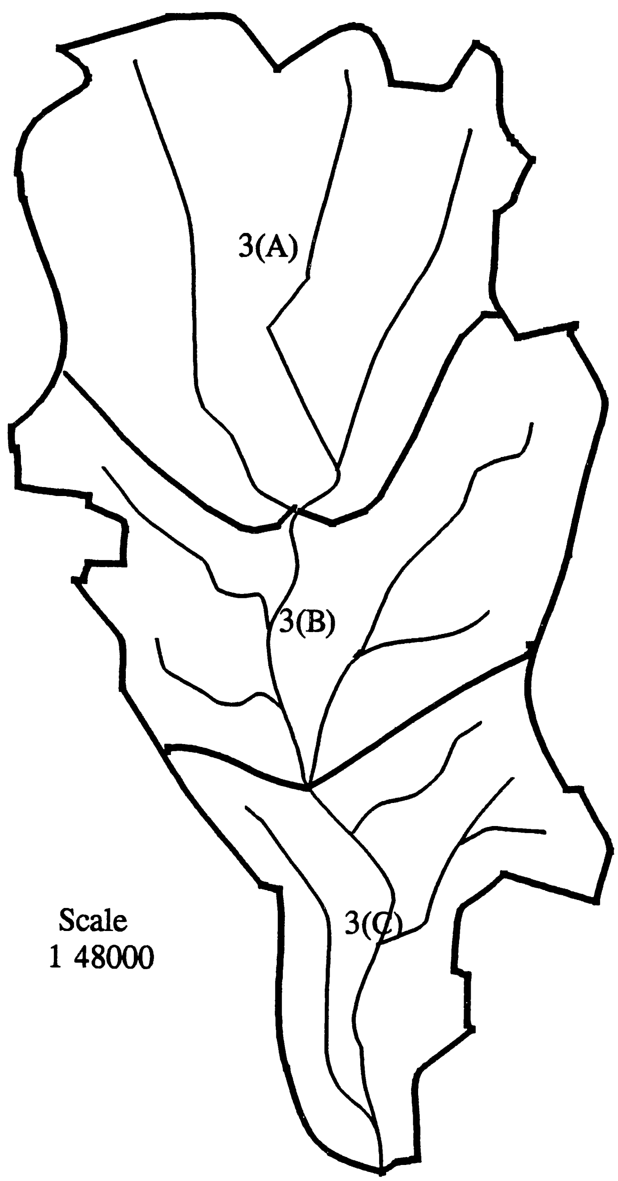

Fıgure 7. The Cow Creek Watershed Dıvıded ınto Three Sub-basıns

impact on major flood events; therefore, the ponds on the watershed were ignored. Once the Cow Creek watershed had been chosen as the data source, the data collection process began.

Data Collection

Data for the watershed data base originated from GRASS and other outside sources. It was intended to first obtain as much data relevant to the watershed as possible from GRASS. Data that was still necessary but unavailable in GRASS was then estimated using other sources. Data that was obtained from GRASS for the watershed included land use and soil type. In addition, areas corresponding to each land use and soil type were determined within GRASS.

GRASS Files

Some of the data files for the Cow Creek watershed data base were created using GRASS. From the land use and soil type data within GRASS, it was possible to estimate the curve number and average slope for the Cow Creek watershed. The soil type data was used to determine the average slope while a combination of the land use and soil type data was used to determine the curve number. GRASS was used to create soil type files and combination files for the watershed data base.

A soil type file and combination file were developed for each sub-basin defined in Figure 6. Because there were six sub-basins, a total of twelve files for the watershed were created. Copies of these files are included in Appendix B in the same form as they existed in the watershed data base. Before GRASS was used to create data files for the Cow Creek watershed, however, the watershed's boundary and location were determined on a map and then digitized.

The Cow Creek watershed area was defined in GRASS by digitizing the watershed boundary. First, the watershed's boundary was manually drawn, based on the topographic contours, onto a 7.5 minute quadrangle map. The watershed boundary on the map was then digitized using the module, Digit. Digit is a program driven by GRASS that stores the boundary data in vector form. After the boundary data was digitized and stored, GRASS was used to convert the boundary data from vector to raster form.

The raster representation of the watershed was used to define the different land uses and soil types that were encompassed within the actual watershed boundary. To match the resolution of the data in the Payne County data files, the grid cell size for the raster watershed area was designated to represent 4 hectares (9.88 acres). Once the raster cell sizes matched, the watershed area was laid onto the soil and land use data layers of Payne County.

Using the overlaying function within GRASS, each of the six sub-basins, in raster form, were laid onto the Payne County data files to define the soil types and land uses that existed within their respective areas. It was found that 44 soil types and 6 land uses were within the entire watershed boundary. All of the soil types found within the Cow Creek watershed are listed in Table 1 in addition to their respective areas, average slopes, and hydrologic soil groups (HSG's). Also, the different land uses found on the watershed with their respective areas are listed in Table 2.

The combination files necessary for determining curve numbers were created within GRASS. However, some of the data required for the files originated from sources other than GRASS. Technically, the curve number is a function of both land use and HSG (Soil Conservation Service, 1972). GRASS was unable to provide the HSG's for the soil types defined in the watershed.

The HSG expresses a range of infiltration rates which each soil type could exhibit. There are four ranges of infiltration rates which are identified as A, B, C, and D (Soil Conservation Service, 1972). The HSG's were determined for the soil types within the Cow Creek watershed using the Payne County Soil Survey. After the HSG's were determined, they were entered into GRASS in replacement of the soil types. In other words, the polygons representing different soil types were replaced with polygons representing HSG's. Once the HSG file for each sub-basin was defined in GRASS, the combination files were created.

The HSG and land use combination files necessary for determining the curve numbers were created in GRASS. The combination files were created by combining the HSG files

TABLE 1

SOIL TYPES FOR THE COW CREEK WATERSHED

Category		Acres	HSG	SLOPE
2	Coyle loam, 1 to 3 percent slo	59	B	2
3	Coyle loam, 3 to 5 percent slo	257	B	4
4	Coyle loam, 2 to 5 percent slo	109	B	4
5	Bethany silt loam, 0 to 2 perc	89	C	1
6	Pulaski fine sandy loam, frequ	613	B	1
10	Darnell-Rock outcrop complex,	69	C	25
11	Stephenville-Darnell complex,	613	B	6
21	Kirkland silt loam, 0 to 2 per	405	D	1
25	Grainola-Lucien complex, 1 to	237	D	3
26	Grainola-Lucien complex, 5 to	652	D	9
32	Harrah-Pulaski complex, 0 to 8	119	B	4
33	Norge loam, 1 to 3 percent slo	188	B	2
34	Norge loam, 3 to 5 percent slo	99	B	4
35	Norge loam, 2 to 5 percent slo	316	B	4
37	Port silt loam, occasionally f	10	B	2
40	Grainola-Ashport complex, 0 to	346	D	4
41	Easpur loam, occasionally floo	306	B	2
42	Ashport silty clay loam, rarel	30	B	2
43	Pulaski fine sandy loam, occas	49	B	2
45	Renfrow silt loam, 1 to 3 perc	109	D	2
46	Renfrow silt loam, 3 to 5 perc	178	D	4
47	Renfrow loam, 2 to 5 percent s	583	D	4
49	Renfrow and Grainola soils, 3-	208	D	5
51	Stephenville fine sandy loam,	10	B	3
53	Stephenville fine sandy loam,	10	B	2
54	Stephenville fine sandy loam,	79	B	4
58	Teller loam, 3 to 5 percent sl	10	B	4
59	Konawa and Teller soils, 2 to	40	B	4
60	Mulhall loam, 3 to 5 percent s	227	B	4
61	Mulhall loam, 3 to 5 percent s	198	B	4
62	Mulhall loam, 3 to 5 percent s	227	B	4
65	Grainola clay loam, 3 to 5 per	40	D	4
66	Masham silty clay loam, 5 to 2	395	D	15
69	Zaneis loam, 1 to 3 percent sl	40	B	2
70	Zaneis loam, 3 to 5 percent sl	109	B	4
71	Zaneis loam, 2 to 5 percent sl	128	B	4
72	Zaneis-Huska complex, 1 to 5 p	208	B	3
73	Dale silt loam, rarely flooded	49	B	2
74	Coyle-Lucien complex, 2 to 5 p	128	B	4
76	Coyle and Zaneis soils, 2 to 5	148	B	4
80	Renfrow-Urban land complex, 1	208	D	3
81	Huska silt loam, 1 to 3 percen	208	D	2
88	Oil-Waste land	10	D	2
94	Doolin silt loam, 0 to 2 perce	20	C	1

TABLE 2

LAND USES FOR THE COW CREEK WATERSHED

Category		Acres
1	Cropland	722
2	Rangeland - Open Grasslands	3620
3	Pasture land	870
4	Forest - Postoak/Blackjack Oak	435
5	Urban Ranchette - House and Lot	119
6	Urban/Built-Up Land	484

and land use files. Using the overlaying function in GRASS, each HSG file was laid onto the corresponding land use file to create a combination file. The combination files contained the areas for each polygon resulting from the overlay process. The combination files that were created in GRASS were then saved and arranged into the watershed data base. The format for the combination files will be discussed in greater detail later in this chapter.

Other Files

Additional files were included in the data base to provide information required by the interface program. Because GRASS could only provide the watershed data base with the soil and combination files, files were developed outside of GRASS and then added to the data base manually.

Two files were created and assembled using a text editor. One file contained the curve numbers for every possible HSG and land use combination determined by GRASS for the Cow Creek watershed. The curve numbers were determined subjectively based on the descriptions provided by the SCS (Soil Conservation Service, 1972). The other file assigned a slope for each soil type. Slopes were estimated from the soils' descriptions found in the SCS Soil Survey for Payne County. Both files are also included in Appendix B. In addition to organizing the data base, a uniform method for presenting the data was necessary to complete the development of the data base.

Data Format

The success of the data transfer from data base to model was dependent upon the ability of the interface to read and extract the proper information from the data files. It was critical that the data be presented in a form that was consistent. A numbering scheme was developed to represent the data for the Cow Creek watershed.

A numbering scheme was organized such that each HSG and land use combination could be identified by a numerical value, assigned to a curve number, and then systematically read by the interface program. Since there were six land uses and four HSG's, there were a total of 24 possible combinations. The hydrologic soil groups A, B, C, and D were assigned the values of 10, 20, 30, and 40 respectively, while the six land uses were assigned the values of one through six which are shown in Table 2.

The combination values were determined by adding the HSG value to the land use value. For example, if a polygon in the combination file represented an area of cropland combined with hydrologic soil group A, the polygon's classification number would be ten plus one or eleven. This method of numbering enables the interface program to recognize every possible combination. However, if another watershed contained more than ten land uses, the numbering scheme would have to be adjusted to accommodate that need.

A numbering scheme was also used to represent the different soil types found on the Cow Creek watershed. The category number that was assigned to each soil type in Payne County by the SCS was also used to identify each soil in the data base. The Payne County Soil Survey identified 99 soils, 44 of which were on the Cow Creek watershed. Using the soil category number, each soil found in Payne County could be identified in the data base.

Summary

Completion of the Cow Creek data base was an essential step prior to designing the interface program. Three steps were required to fully develop the data base. The first step was to choose the Cow Creek watershed as the watershed of study and make appropriate assumptions about its characteristics. The second step was to assemble all of the spatial data from the Cow Creek watershed and organize it into an useable form. The last step was to develop a numbering scheme that could adequately represent all of the data.

CHAPTER IV

DEVELOPING THE INTERFACE PROGRAM

Introduction

As used in this study, an interface program is an automated system that links two software packages by transferring or translating information. Use of an interface can provide a systematic process of transferring information which decreases user interaction and increases speed and efficiency. This chapter describes the development of an interface that links GRASS and HEC-1.

The interface was developed to assist in the process of determining parameter values for HEC-1. The interface accessed data stored in a watershed data base, used that data to calculate parameter values, and then automatically entered the parameter values into a HEC-1 input file. Parameter estimation was achieved through the use of subroutines that utilize data stored in a watershed data base.

Estimating Parameters

Using the data within the watershed data base, the interface estimated parameters based on both theoretical and empirical relationships. The interface was designed to determine the basin area and two hydrologic parameters, weighted curve number and lag time. It should be mentioned, however, that an interface is not necessarily limited to these three parameters. More parameters could have been determined if more watershed data had been available in the GRASS data bases. At the time of study, the data within the GRASS data bases could only support the area, lag time, and curve number parameters. However, the interface was designed in such a way that if more data were available, additional parameters could have been estimated.

The interface program was designed so that each parameter was determined using a separate subroutine. The source code for the interface program is included in Appendix A. Use of subroutines allows for future program expansion in the case that data necessary for determining other parameters is available. For each additional parameter, a new subroutine would simply be added to the interface program without modifying any other parts of the program.

This technique also applies if a different method is preferred for describing a hydrologic process. For example, if the user wants to determine rainfall loss using the Holton method rather than the curve number method, a new subroutine would be added to the program to facilitate the Holton method. As the program grows, the number of options will increase which will provide the user with more alternatives providing greater flexibility in estimating parameters. Each of the three parameters currently determined by the interface program are also discussed to provide a better understanding of how they are estimated.

Weighted Curve Number

The curve number method was developed by the SCS to describe the amount of rainfall lost through infiltration and initial abstractions. Curve numbers range in value from 0 to 100. The SCS established that the lower the infiltration losses, the greater the curve number value. For example, parking lots are typically assigned curve number values of 98 (Soil Conservation Service, 1975). The interface assigned curve number values to the watershed combinations based on the same principles as defined by the SCS.

The interface read the HSG and land use combinations and respective areas from the files and incorporated the values into arrays. Each sub-basin or watershed had a separate array. The first column of the array included the combination values while the second column included the combination's areas. If the interface read a combination value of 21 with an area of 10 acres, a value of 10 would be entered into cell (21,2) of the array. Once all the areas for the combinations were entered into the array, the interface assigned a curve number to each combination.

The interface used the curve number attribute file to ascertain a curve number for each combination. The interface scanned down the attribute file looking for combination values that were present on the sub-basin of interest. When the interface recognized a combination that was present on the sub-basin, the interface read the corresponding curve number value for that combination. The interface then entered the curve number into the third column of the array adjacent to the curve number's respective area and combination value. After the three columns of the array were completed, the weighted curve number was calculated.

The weighted curve number reflects several curve numbers on a sub-basin. It represents the effective curve number for a whole sub-basin that includes areas with different curve numbers. The interface estimated the weighted curve number, WCN, from the equation

$$WCN = \sum_{i=1}^{n} \frac{A_i}{A_T} CN_i \qquad (1)$$

where n is the number of combinations in the given sub-basin, A_i and CN_i are the area and curve number of the i^{th} combination respectively, and A_T is the sub-basin area. After calculating the weighted curve number, the interface then entered this value into the HEC-1 input file adjacent to the "LS" identifier. The "LS" identifier's location can be seen in the HEC-1 input files included in Appendix C.

Lag Time

Lag time is one of several variables used to determine the peak time for a hydrograph (Soil Conservation Service, 1973). Lag time is an approximation of the mean travel time for overland flow on a watershed or sub-basin (Schwab et al., 1981). The interface estimated the lag time from the equation

$$T_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}} \qquad (2)$$

where T_L is the lag in hours, L is the hydraulic length of the sub-basin in feet, S is related to the weighted curve number by equation 3, and Y is the average land slope of the sub-basin (Soil Conservation Service, 1975). The interface calculated the variables in equation 2 based on both data stored in the watershed data base and data entered by the user.

Two options were offered for determining the hydraulic length of each sub-basin. The first option estimated the hydraulic length using size files created by GRASS. These size files contained information relating to the number of rasters that made up each sub-basin in both the X and Y direction. If the first option was chosen to determine the hydraulic length, the interface assumed that the water flowed in the y direction. Then, the interface counted the number of rasters in the y direction, multiplied them by the length of the rasters and by the assumed sinuosity of the flow channel. For the Cow Creek watershed, the length of the rasters was determined to be 656 feet and the sinuosity of any flow channel on the watershed was assumed to be 1.5. If the user does not feel that water moves in the y direction, the second option should be chosen.

The second option to determine the hydraulic length merely prompts the user for a value. If the second option is chosen, the user must use personal knowledge of the watershed or some other outside source to estimate the hydraulic length. The only disadvantage to the second option is that it does not offer the automation of the first option.

The S variable in equation 2 was automatically determined by the interface. Hence, no user interaction was necessary for estimating this variable. The interface used the equation

$$S = \frac{1000}{WCN} - 10 \qquad (3)$$

where WCN is the weighted curve number determined from equation 1 (Soil Conservation Service, 1972). For each sub-basin, a different S was determined because each sub-basin had a different weighted curve number.

The interface automatically determined the average slope for each sub-basin to provide equation 2 with the final variable, Y. To determine the average slope for a sub-basin, an array was used in the same manner as for the weighted curve number. Again, each sub-basin had its own array. The first column of the array contained the category numbers for each soil type in Payne County while the second column contained the soil type areas for only the sub-basin of interest. The interface read the areas for a particular sub-basin and placed them in the second column next to the respective soil category number in the first column. The interface then read the soil slope attribute file to obtain the slope data for each soil located in the sub-basin of interest. The interface scanned down the attribute file until it recognized a soil type from the sub-basin. The slope for that soil type was then entered into the third column of the array adjacent to its respective area and soil category number. After the array was completed, the interface determined the average slope for the sub-basin.

The value determined by the interface was a weighted average slope. The calculations used to determine the value were similar to that of the weighted curve number. The interface used the equation

$$Y = \sum_{i=1}^{n} \frac{A_i}{A_T} S_i \qquad (4)$$

where Y is the average slope, n is the number of soil types on the sub-basin, A_i and S_i are the area and slope of the i^{th} soil type respectively, and A_T is the total area of the sub-basin in acres. After the lag time was calculated, the interface automatically entered the value into the HEC-1 input file. The values location in the input file was next to the "UD" identifier.

Basin Area

The basin area represented the area of a watershed or sub-basin. The interface was designed so that the basin area was determined in the same subroutine as the weighted curve number. A separate subroutine for the basin area was not necessary because it was already determined in the form of A_T from equation 1. To determine the basin area, the interface used the equation

$$BA = \frac{\sum_{i=1}^{n} A_i}{640} \qquad (5)$$

where BA is the basin area in square miles, n is the number of combinations in the sub-basin, and A_i is the area of the i^{th} combination in acres. The basin area was converted into square miles because those were the units required by HEC-1. After calculating the basin area, the interface placed the value next to the "BA" identifier in the HEC-1 input file.

Combining Sub-basin Data

A special subroutine that combined data from any number of sub-basins was included in the interface. The purpose for including the subroutine in the interface was to provide an automated method that varied the number of sub-basins for a particular watershed. Using this subroutine, the effects that the number of sub-basins have on a watershed hydrograph could be studied. It should be noted, however, that this subroutine was not necessary for any of the other functions performed by the interface.

Two arrays were used by the interface to combine sub-basin data. One array contained the soil type data for the combined sub-basins while the other array contained the combination data for the combined sub-basins. The user initiated the combining process by entering the number of sub-basins to be combined. The data from each sub-basin was sequentially added to the data from the previous sub-basin in the arrays. After all of the data had been added into the arrays and totalled, the interface created two new files for the combined sub-basins referred to as the soil type and combination files. The weighted curve number, basin area, and lag time for the combined sub-basins could then be calculated using the other subroutines.

Summary

The rational behind the interface program is to provide a systematic and efficient method for determining hydrologic parameters for any watershed. An interface program offers the advantage of decreasing the manual labor that is typically required when conducting a hydrologic analysis for a given watershed. For a completely developed interface, the only factor that limits its operation is data. In other words, as long as ample data is present within the data base, the interface program can always determine the parameters and enter them into the model's input file. User experience or knowledge does not limit the operations of a true interface program. Overall, the interface program offers an alternative method for determining parameters that is automated and easy to use.

CHAPTER V

PREPARING THE HEC-1 INPUT FILES

Introduction

Three separate input files were created to represent the Cow Creek watershed. Each input file represented the watershed divided into a different number of sub-basins. For this project, the watershed was divided into one, three, and six sub-basins which were referred to by the files Cow1, Cow3, and Cow6 respectively. Although all three files represented the same watershed, each input file required a different number of parameters depending on the number of sub-basins it represented. The number of parameters required by the model was directly proportional to the number of sub-basins. Therefore, the input file representing the watershed as six sub-basins required a lot more parameters than the input file representing the watershed as one sub-basin.

Each input file was used to provide the HEC-1 model with three types of information for describing the Cow Creek watershed. The three types of information included: methods used for modeling hydrologic processes, physical relationships between the different parts of the watershed, and numeric values for the parameters required by each method. A two step process was performed in order to develop complete HEC-1 input files capable of expressing the three types of information.

Organizing the Identifiers

The first step was to organize the identifiers. This was performed using the program, HEC1IN (Corps of Engineers, 1990). HEC1IN is a program that is included in the HEC-1 software package for the purpose of providing an automatic method for organizing the identifiers. HEC1IN incorporated two of the three types of information into the input files.

HEC1IN specified the methods used for modeling the hydrologic processes in addition to the physical relationships between the different parts of the Cow Creek watershed. As the methods were chosen by the user, HEC1IN placed the identifiers corresponding to those same methods into the input file. HEC1IN then arranged the chosen identifiers into a certain order which reflected the physical relationships of the different watershed parts. The final product of the HEC1IN program was a skeleton input file which contained the necessary identifiers for representing the chosen methods to be used by the model and for explaining the physical relationships of the Cow Creek watershed. The three input files are shown in Appendix C.

Parameter Values

The next step was to supply values for the parameters which corresponded to each identifier. In other words, each identifier had a different set of parameters depending on what it represented. The interface was first used to enter parameter values automatically into the input files. The parameters that were outside of the interfaces capability but required by HEC-1 were manually determined and entered into the input files. Recalling from the previous chapter, the interface could determine the parameter values for rainfall loss, basin area, and the runoff hydrograph.

Rainfall Loss

Rainfall losses for the watershed were determined using the SCS Curve number method. The identifier representing this method was "LS". The "LS" identifier required two parameter values, curve number and impervious area. Both of the parameter values were automatically entered next to the "LS" identifiers using the interface program. The curve number values for each of the sub-basins defined by files Cow1, Cow3, and Cow6 are listed in Tables 3, 4, and 5. All of the parameter values for the "LS" identifiers were based on data stored in GRASS.

Basin Area

The area of each sub-basin was identified by "BA". The number of "BA" identifiers listed in the input files equaled the number of sub-basins represented by that file. The "BA" identifier required only the basin area value. Each basin area value was automatically entered into the input files by the interface. The areas corresponding to the sub-basins are also listed in Tables 3, 4, and 5.

Runoff Hydrograph

Runoff hydrographs for the Cow Creek watershed were determined using the SCS dimensionless unit hydrograph method (Soil Conservation Service, 1972). The "UD" identifier was used to represent the SCS method. A "UD" identifier was present for each sub-basin because each sub-basin had its own hydrograph. The time increment for all hydrographs was specified at the "IT" identifier. The time increment was dependent upon the smallest of the six lag times determined for the sub-basins defined by Cow6. Using the smallest lag time, the time increment was determined from the equation

$$\Delta t < .29(t_L) \tag{6}$$

where t_L is the lag time (Corps of Engineers, 1990). Based on the lag times shown in Table 3, it was decided to use a time increment of 15 minutes.

The only parameter value required for the "UD" identifiers was the lag time which was automatically entered by the interface into the Cow1, Cow3, and Cow6 input files. All lag times calculated by the interface were based on equation 2. The lag time values are included in Tables 3, 4, and 5. The remaining identifiers which represented the

TABLE 3

PARAMETER VALUES FOR THE COW CREEK WATERSHED AS SIX SUB-BASINS

Parameter	Sub-basins 6(A)	6(B)	6(C)	6(D)	6(E)	6(F)
Area(sq.mi.)	2.3	2.1	2.2	1.9	1.6	2.6
Curve Number	74	77	80	84	76	81
Lag Time(hrs)	1.6	1.8	1.6	1.3	2.6	2.0
Hyd. Length(ft)	20,000	18,000	20,000	17,500	20,600	24,000
S	3.5	3.0	2.5	1.9	3.1	2.4
Avg. Slope(%)	6.8	3.8	4.8	4.5	2.2	3.9

TABLE 4

PARAMETER VALUES FOR THE COW CREEK WATERSHED AS THREE SUB-BASINS

Parameter	Sub-basins 3(A)	3(B)	3(C)
Area(sq.mi.)	4.5	4.0	4.2
Curve Number	76	82	79
Lag Time(hrs)	1.7	1.5	2.3
Hyd. Length(ft)	20,000	20,000	24,000
S	3.2	2.2	2.7
Avg. Slope(%)	4.9	4.2	2.6

TABLE 5

PARAMETER VALUES FOR THE COW CREEK
WATERSHED AS ONE SUB-BASINS

Parameter	Sub-basin A
Area(sq.mi.)	13
Curve Number	79
Lag Time(hrs)	3.5
Hyd. Length(ft)	50,000
S	2.7
Avg. Slope(%)	4.5

storm pattern and channel routing were determined from sources other than GIS and then manually entered into the HEC-1 input files.

Storm Pattern

Rainfall data for the Cow Creek watershed were determined using the Synthetic Storm method (Corps of Engineers, 1990). Using this method, HEC-1 created a hypothetical storm based on a given duration and return period. The rainfall pattern was constructed by HEC-1 for the 15 minute time increments by a log-log interpolation of the values listed in Table 6. The rainfall depths for the time increments were then arranged to produce a triangular distribution which placed the maximum depth for any given duration at the center of the storm. The amount of rainfall produced from the synthetic storm was dependent upon the chosen storm's magnitude.

The rainfall pattern for this particular project was based on a storm that had a 24-hour duration and a 25-year return period. For a storm of this magnitude, HEC-1 required rainfall depths for the durations of .083, .25, 1, 2, 3, 6, 12, and 24 hours. The depths for the given durations were taken from the TP-40 maps prepared by the United States Weather Bureau (Hershfield, 1961). These depths are shown in Table 6. Once the depth-duration data were determined, they were entered into the HEC-1 input file next to the "PH" identifiers. It should be noted that HEC-1

TABLE 6

DEPTH-DURATION DATA FOR THE
COW CREEK WATERSHED

Duration(hrs)	.083	.25	1	2	3	6	12	24
Depth(inches)	0	2.5	3.2	3.8	4.3	5.0	5.9	6.8

required a "PH" identifier for each sub-basin. Therefore, the same depth-duration values were entered next to each of the "PH" identifiers.

Channel Routing

Channel routing was applied to this project for the purpose of describing water movement from the upper sub-basins to the watershed's outlet. Lower sub-basins which were connected to the watershed's outlet did not require routing. Therefore, when the Cow Creek watershed was not broken into sub-basins, no channel routing was required.

For the Cow Creek watershed, two channels, A and B, were identified. Their locations on the Cow Creek watershed are shown in Figure 5. Channel A begins at point one and ends at point two while Channel B begins at point two and ends at the watershed's outlet. The channel dimensions and characteristics for the two reaches are shown in Table 7. Dimensions for the two channels were obtained from measurements taken at points one and two. These dimensions were assumed to be constant for the entire length of each channel. This was a necessary assumption because channel velocity was estimated using equation 7 which requires that the channel be uniform. Equation 7 is referred to as Mannings equation and expressed as

$$V = \frac{1.49}{n} R^{0.667} S^{0.5} \qquad (7)$$

where V is in fps, n is the roughness coefficient, R is the hydraulic radius in feet, and S is the channel slope.

Channel routing was performed using the Muskingum method (Corps of Engineers, 1960) for both reaches, A and B. The identifier for the Muskingum method was "RM" which required the two parameters, K and x. Both K and x were determined for each channel based on each channel's characteristics. The parameter K was evaluated for both channels using the equation

$$K = \frac{3}{5}\frac{L}{V} \tag{8}$$

where V is the velocity determined from equation 7 and L is the reach length. The parameter x was evaluated using the equation

$$x = \frac{1}{2} - \frac{3}{10}\frac{A}{SLT}(1 - \frac{4}{9}F^2) \tag{9}$$

where S is the channel slope, T is the top width of the channel in feet, and F is the Froud number determined from equation 10 (Corps of Engineers, 1960). The Froud number was determined from the equation

$$F^2 = \frac{Q^2T}{gA^3} \tag{10}$$

where g is 32.2 ft/sec^2. After the K and x parameters were determined for both reaches, they were entered into their respective positions next to the "RM" identifiers. The values for the K and x parameters are also shown in Table 7.

TABLE 7

CHANNEL DIMENSIONS AND PARAMETERS

Parameters	Channel A	B
Shape	Trapezoid	Trapezoid
Bottom Width(ft)	12	15
n	.035	.030
Depth(ft)	11	17
Side Slope	3	2
Slope(%)	.2	.1
Q_{Peak}	3000	6000
Velocity(fps)	6.3	6.9
Area(sq.ft.)	495	833
Length(ft)	12000	21000
K(hrs)	.32	.51
x	.43	.37

Summary

The HEC-1 input file was the last major component necessary for operating the interface system. The first step was to create a skeleton input file using HEC1IN. The skeleton file specified the information pertaining to the physical aspects of the Cow Creek watershed in addition to the preferred methods for calculating hydrologic processes. After the skeleton file was completed, parameter values were entered into the input files using the interface and manual methods.

The interface was used to enter parameter values based on data stored in GRASS. The interface entered the curve numbers, basin areas, and the lag times. For this project, channel routing and storm pattern data were manually entered into the input file. The Muskingum method was used to model channel flow and a synthetic storm was used to create a rainfall pattern. Once the input file was completed, the HEC-1 model could be used to produce hydrographs which represent different numbers of sub-basins on the Cow Creek watershed.

CHAPTER VI

RESULTS AND DISCUSSION

Hydrograph Analysis

Runoff hydrographs for the Cow Creek watershed were studied to determine how the number of sub-basins impacted runoff. After the input files Cow1, Cow3, and Cow6 had been completed, HEC-1 was used to determine a runoff hydrograph for each scenario. Each hydrograph determined by HEC-1 was plotted on a common graph as shown in Figure 8. After the hydrographs were plotted, they were analyzed to determine any affects that may have resulted from varying the number of sub-basins on the watershed.

The affects were determined by comparing each hydrograph's runoff volume, peak time, and peak flow. Values for the three variables of each hydrograph are shown in Table 8. The peak times and peak flows were determined by reading the values directly from the hydrographs. The runoff volume for each hydrograph was found using the equation

$$V = \frac{(12)\,(\Delta t)\,(\sum q_i)}{(A)\,(43560)} \qquad (11)$$

where V is the volume of runoff in inches, the time interval is in seconds, q_i is a hydrograph ordinate in cfs, and A is

TABLE 8

VALUES REPRESENTING CHARACTERISTICS OF THE HYDROGRAPHS

	Cow1	Cow3	Cow6
No. of Sub-basins	1	3	6
Peak Flow(cfs)	5400	8100	8630
Peak Time(hrs)	16.00	14.75	14.50
Volume(inches)	4.32	4.37	4.37

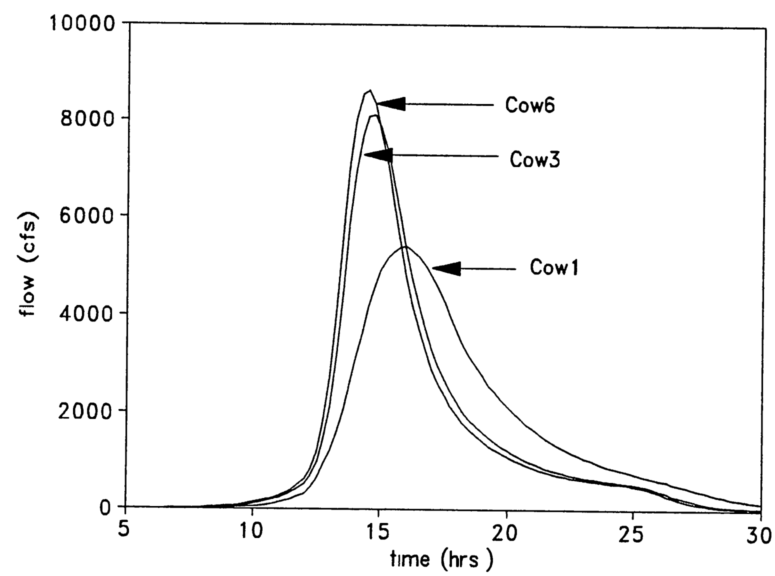

Figure 8 Hydrographs Resulting from Cow1, Cow3, and Cow6

the area in acres.

It can be seen from Table 8 that the peak flows and the peak times for Cow3 and Cow6 were similar. However, the peak flow and peak time for Cow1 were significantly different as compared to those of Cow3 and Cow6. To explain the similarities and differences of the three hydrographs, the methods used to determine the parameter values for each input file were examined.

Recalling from Chapter 4, the lag times for the sub-basins were determined from equation 2. The total lag time for Cow1 was based on the SCS equation while the total lag times for Cow3 and Cow6 were based on both equation 2 and channel flow. Channel flow was incorporated into the total lag times for Cow3 and Cow6 when channel routing was used to model water movement from the upper sub-basins. Cow1 did not consider channel flow because channel routing was not performed. To determine if this difference in describing water movement was the cause of the variations in the hydrographs, a new method was used to determine the total lag time for Cow1.

For Cow1, the lag time was recalculated using a method other than equation 2 and then manually entered into the input file. As shown in Figure 5, water traveling from the most remote location would move through channels A and B. Therefore, the lag time was dependent upon the velocities within the two channels. The total lag time for Cow1 was determined using the equation

$$T_L = .6\left(\frac{L_A}{V_A}+\frac{L_B}{V_B}\right)+T_{L6(B)} \tag{12}$$

where V is the velocity in fps determined from equation 7, L is the length of the channel in feet, and $T_{L6(B)}$ is the lag time for sub-basin 6(B) in hours. The purpose of equation 12 was to incorporate the effects of channel characteristics into the lag time value for Cow1.

Based on equation 12, a new lag time of 2.6 hours was calculated and entered into the Cow1 input file. Using the new lag time, another hydrograph was then determined for Cow1 and plotted with the Cow3 and Cow6 hydrographs as shown in Figure 9. The new hydrograph's peak time, peak flow, and runoff volume are shown in Table 9.

The results in Table 9 showed that a consistent method for determining lag times for the Cow Creek watershed was critical in maintaining similar peak times for different numbers of sub-basins. As seen in Table 9, the peak times for the hydrographs were similar because flow within a channel was considered for all three conditions. Although the three hydrographs in Figure 9 were based on channel flow, the peak flow for Cow1 was still significantly less than the Cow3 and Cow6 peak flows.

Sensitivity Analysis

A sensitivity analysis was performed to determine which parameters were the most influential in the hydrograph. For this particular test, the curve numbers, average land

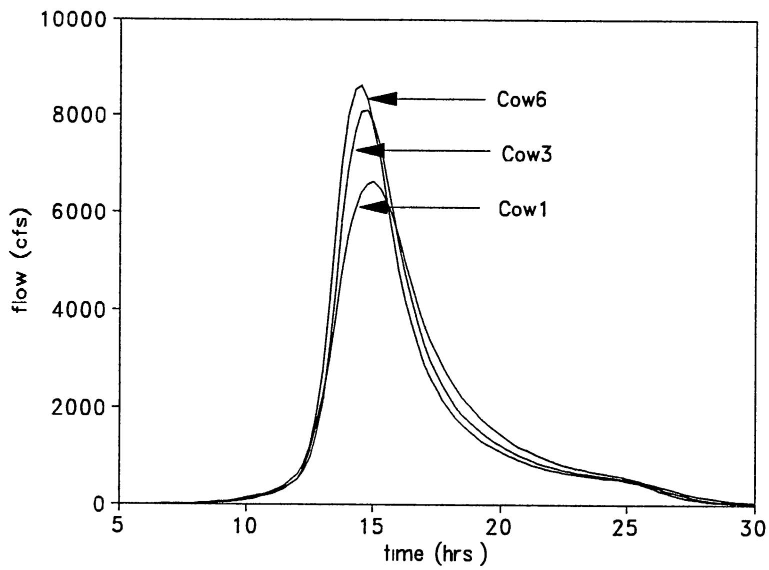

Figure 9 Hydrographs Resulting After Cow1's Lag Time Adjustment

TABLE 9

VALUES REPRESENTING CHARACTERISTICS OF THE NEW HYDROGRAPHS

	Cow1	Cow3	Cow6
No. of Sub-basins	1	3	6
Peak Flow(cfs)	6630	8100	8630
Peak Time(hrs)	15.00	14.75	14.50
Volume(inches)	4.32	4.37	4.37

slopes, and channel roughness coefficients were increased and decreased ten percent. Each parameter was varied while the other two remained constant. This process was performed for all three input files. The results of the analysis are shown in Table 10.

The results show that the curve number has the greatest impact on both peak flow and peak time. The results also show that all three parameters exert some influence on the peak time and peak flow. Graphs that depict each condition are included within Appendix D to illustrate how each parameter variation affects the hydrographs.

Summary

The lag times used to produce the first set of hydrographs were determined using inconsistent methods because channel flow was not considered for Cow1. This inconsistency prompted a new method for calculating the lag time for Cow1. This new method considered channel flow similar to the channel routing procedures used in Cow3 and Cow6. The hydrograph resulting from the new lag time had a similar peak time, but the peak flow was still significantly less than those for the other two hydrographs.

After determining that the methods used to model water movement on the watershed were consistent, a sensitivity analysis was performed to determine how the curve number, land slope, and channel roughness coefficient affected the runoff hydrograph. It was found that all three parameters

TABLE 10

VALUES RESULTING FROM THE SENSITIVITY ANALYSIS

	Cow1	Cow3	Cow6
Base Conditions			
Peak Flow(cfs)	6630	8100	8630
Peak Time(hrs)	15.00	14.75	14.50
Volume(inches)	4.32	4.37	4.37
Roughness Coeff.			
+10%			
Peak Flow(cfs)	6430	8100	8580
Peak Time(hrs)	15.00	14.75	14.50
Volume(inches)	4.32	4.37	4.37
-10%			
Peak Flow(cfs)	6800	8150	8660
Peak Time(hrs)	14.75	14.50	14.25
Volume(inches)	4.32	4.37	4.37
Curve Number			
+10%			
Peak Flow(cfs)	9220	11500	11900
Peak Time(hrs)	14.25	14.25	14.00
Volume(inches)	5.20	5.26	5.24
-10%			
Peak Flow(cfs)	4850	5520	5980
Peak Time(hrs)	15.25	15.25	15.00
Volume(inches)	3.48	3.53	3.54
Land Slope			
+10%			
Peak Flow(cfs)	7040	8420	8990
Peak Time(hrs)	14.75	14.50	14.25
Volume(inches)	4.32	4.37	4.37
-10%			
Peak Flow(cfs)	6430	7850	8360
Peak Time(hrs)	15.00	14.75	14.50
Volume(inches)	4.32	4.37	4.37

had some impact on the peak flow and peak time. However, the curve number had the greatest impact on the peak flow and peak time.

CHAPTER VII

SUMMARY AND RECOMMENDATIONS

Summary

An interface program was designed to use data from a GIS to calculate parameter values and enter those values into a hydrologic model's input file. The interface used in this project accessed data from the Cow Creek watershed data base and used that data to determine values for the basin area, curve number and lag time parameters. Some of the data used to determine the parameters originated from GRASS. The interface then automatically entered the three parameter values into their proper locations into the HEC-1 input file.

This process has shown that data stored in a GIS can be successfully accessed and used to determine parameter values for a hydrologic model. Also, the interface has proved to be a powerful tool for decreasing the data collection effort. By reducing this effort, hydrologic processes, such as sub-basin effects, can be studied more thoroughly.

Hydrographs that were initially produced for the Cow Creek watershed were used to determine the affects that the number of sub-basins had on the runoff hydrographs. It was found that the number of sub-basins on the Cow Creek watershed had a greater impact on the runoff hydrograph when different methods were used to determine basin lag time. After the methods were adjusted to maintain consistency, the number of sub-basins had less of an impact on the total runoff hydrograph.

Recommendations

Although three parameters were estimated, more subroutines can be added to the interface to determine additional parameters such as channel routing or reservoir routing. Routines can also be developed to facilitate other methods used to model hydrologic processes. The addition of more subroutines would greatly enhance the interface's overall performance.

In addition, the format of the interface can be adjusted to read files produced by a GIS other than GRASS. If another GIS has the capacity to maintain greater amounts of data than GRASS, it would behove the user to use the other GIS as a data source.

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APPENDIXES

APPENDIX A

COMPUTER CODE FOR THE INTERFACE PROGRAM

```
************************************************************
*   PROGRAM VERSION FOR MULTIPLE SUB-BASIN WATERSHED       *
**********   by G.R. NORRIS for THEISIS PROJECT  ***********
************************************************************
      REAL TOTAL,TLAG,WCN,WSL
      INTEGER SUB,SUBB,CHO
      CHARACTER*20 CARD*80,BA,LS,UD,CNAME,SNAME,SKEL,TSKEL
      CHARACTER*20 FILE1,FILE2
      SUB=1
      WRITE(*,5)
    5 FORMAT(/2X,'HOW MANY SUB-BASINS IN THE WATERSHED?'/2X)
      READ(*,*)SUBB
      WRITE(*,8)
    8 FORMAT(//2X,'ENTER THE CURVE NUMBER DATA FILE'/1X,
     $' NAME WITH DRIVE LETTER THAT WILL BE USED IN THE
     $' ANALYSIS.'/2X)
      READ(*,'(A)')CNAME
      WRITE(*,10)
   10 FORMAT(//2X,'ENTER THE SOIL/SLOPE DATA FILE NAME'/1X,
     $' WITH DRIVE LETTER THAT WILL BE USED IN THE
     $' ANALYSIS.'/2X)
      READ(*,'(A)')SNAME
      WRITE(*,15)
   15 FORMAT(//2X,'ENTER NAME OF HEC-1 SKELETON FILE'/2X)
      READ(*,'(A)')SKEL
      WRITE(*,20)
   20 FORMAT(//2X,'WHAT IS THE NAME OF THE TEMPORARY'/1X,
     $' HEC-1 SKELETON FILE?'/2X)
      READ(*,'(A)')TSKEL
      WRITE(*,25)
   25 FORMAT(//2X,'DO YOU WANT TO COMBINE ANY'/1X,
     $'SUB-BASINS BEFORE YOU START THE PROGRAM?'//1X,
     $' 1) YES'/1X,
     $' 2) NO')
      READ(*,*)CHO
      IF(CHO.EQ.2)GOTO 28
      CALL COMB(FILE1,FILE2)
   28 OPEN(UNIT=12,FILE=SKEL,STATUS='UNKNOWN')
      OPEN(UNIT=13,FILE=TSKEL,STATUS='UNKNOWN')
      DO 150 K=1,SUBB
      CALL CNA(WCN,TOTAL,SUB,CNAME)
      CALL LAG(TLAG,WCN,TOTAL,SUB,SNAME,WSL)
   30 READ(12,'(a)')CARD
      BA='BA     0'
      LS='LS'
      UD='UD'
      IF(CARD.EQ.'BA     0')GOTO 34
      IF(CARD.EQ.'LS')GOTO 36
      IF(CARD.EQ.'UD')GOTO 38
      WRITE(13,'(A)')CARD
      GOTO 30
   34 WRITE(13,35)TOTAL
   35 FORMAT('BA',2X,F4.1)
```

```
      GOTO 30
   36 WRITE(13,37)WCN
   37 FORMAT('LS',5X,'0',4X,F4.1,7X,'0')
      GOTO 30
   38 WRITE(13,39)TLAG
   39 FORMAT('UD',2X,F4.1)
      WRITE(*,45)SUB,TOTAL,TLAG,WCN,WSL
   45 FORMAT(//2X,'DATA SUMMARY FOR SUB-BASIN #',I2/1X,
     $'   BASIN AREA= ',F4.1,' SQ. MILES'/1X,
     $'   LAG TIME=    ',F8.1,' HOURS'/1X,
     $'   WEIGHTED CURVE NUMBER=',F4.1/1X,
     $'   AVERAGE SLOPE =',F4.1)
      WRITE(*,46)
   46 FORMAT(//2X,'DO YOU ACCEPT THESE VALUES?'/1X,
     $'   1)CONTINUE'/1X,
     $'   2)BETTER THINK ABOUT IT')
      READ(*,*)CHO
      IF(CHO.EQ.2)GOTO 195
      SUB=SUB+1
  150 CONTINUE
  152 READ(12,'(A)',END=155)CARD
      WRITE(13,'(A)')CARD
      GOTO 152
  155 CLOSE(UNIT=12)
  160 CLOSE(UNIT=13)
      OPEN(UNIT=13,FILE=TSKEL,STATUS='OLD')
      OPEN(UNIT=12,FILE=SKEL,STATUS='OLD')
  180 READ(13,'(A)',END=185)CARD
      WRITE(12,'(A)')CARD
      GOTO 180
  185 CLOSE(UNIT=13)
      CLOSE(UNIT=12)
  195 END
************************************************************
************ WEIGHTED CURVE NUMBER AND BASIN AREA **********
************              CALCULATIONS            ***********
************************************************************
      SUBROUTINE CNA(WCN,TOTAL,SUB,CNAME)
      INTEGER K,SUB,OVER,CN
      CHARACTER*20 FNAME,CNAME
      REAL AREA,A(500,3),I,TOTAL,WCN
      I=1
      TOTAL=0
      DO 201 K=1,500
       A(K,1)=0
       A(K,2)=0
       A(K,3)=0
  201 CONTINUE
      WRITE(*,205)SUB
  205 FORMAT(//2X,'ENTER GRASS OVERLAY FILE FOR'1X/,
     $' SUB-BASIN #',I2)
      READ(*,'(A)')FNAME
      OPEN(UNIT=10,FILE=FNAME,STATUS='UNKNOWN')
```

```
      DO 210 K=1,6
      READ(10,208)
  208   FORMAT(/)
  210 CONTINUE
  213 READ(10,215,ERR=222)OVER,AREA
  215 FORMAT(4X,I2,35X,F12.2)
  217 IF(I.EQ.OVER)GOTO 218
      I=I+1
      GOTO 217
  218 TOTAL=TOTAL+AREA
      A(I,1)=OVER
      A(I,2)=AREA
      GOTO 213
  222 CLOSE (UNIT=10)
      OPEN(UNIT=11,FILE=CNAME,STATUS='UNKNOWN')
      I=1
  226 READ(11,227,END=240)OVER,CN
  227 FORMAT(I2,2X,I2)
  228 IF(I.EQ.OVER)GOTO 230
      I=I+1
      GOTO 228
  230 A(I,3)=CN
      GOTO 226
  240 CLOSE (UNIT=11)
      WCN=0
      DO 250 I=1,100
      IF(A(I,2).EQ.0)GOTO 250
      WCN=WCN+(A(I,2)/TOTAL)*A(I,3)
  250 CONTINUE
      RETURN
      END
************************************************************
***********          LAG TIME CALCULATIONS    ***************
************************************************************
      SUBROUTINE LAG(TLAG,WCN,TOTAL,SUB,SNAME,WSL)
      REAL WSL,B(100,3),S,YL,LEN,TLAG,AREA,TOTAL
      INTEGER SOIL,I,SLOPE,SUB,CH1
      CHARACTER*20 FNAME,SNAME
      I=1
      WSL=0
      DO 301 K=1,100
       B(K,1)=0
       B(K,2)=0
       B(K,3)=0
  301 CONTINUE
      WRITE(*,306)SUB
  306 FORMAT(//2X,'ENTER SOIL DATA FILE FOR SUB-BASIN #',I2)
      READ(*,'(A)')FNAME
      OPEN(UNIT=14,FILE=FNAME,STATUS='UNKNOWN')
      DO 310 K=1,6
      READ(14,308)
  308 FORMAT(/)
  310 CONTINUE
```

```
313 READ(14,315,ERR=322)SOIL,AREA
315 FORMAT(4X,I2,35X,F12.2)
317 IF(I.EQ.SOIL)GOTO 318
    I=I+1
    GOTO 317
318 B(I,1)=SOIL
    B(I,2)=AREA
    GOTO 313
322 CLOSE(UNIT=14)
    I=1
    OPEN(UNIT=15,FILE=SNAME,STATUS='UNKNOWN')
326 READ(15,327,END=340)SOIL,SLOPE
327 FORMAT(I2,2X,I2)
330 B(I,3)=SLOPE
    I=I+1
    GOTO 326
340 CLOSE(UNIT=15)
    WSL=0
    DO 350 I=1,100
    IF(B(I,2).EQ.0)GOTO 350
    WSL=WSL+(B(I,2)/TOTAL)*B(I,3)
350 CONTINUE
    S=(1000/WCN)-10
    WRITE(*,352)
352 FORMAT(//2X,'DO YOU THINK THAT THE .HDR FILE CAN'/1X,
   $'  BE USED TO REPRESENT THE LONGEST WATER COARSE?'/1X,
   $'  0) YES'/1X,
   $'  1) NO'/2X)
    READ(*,*)CH1
    IF(CH1.EQ.0)GOTO 359
    WRITE(*,354)SUB
354 FORMAT(2X,'ENTER VALUE FOR LONGEST HYDRAULIC PATH'/1X,
   $' IN SUB-BASIN #',I2,' IN FEET.')
    READ(*,*)LEN
    GOTO 397
359 WRITE(*,360)SUB
360 FORMAT(//2X,'ENTER .HDR FILE NAME FOR SUB-BASIN #',I2)
    READ(*,'(A)')FNAME
    OPEN(UNIT=16,FILE=FNAME,STATUS='UNKNOWN')
    DO 390 K=1,2
    READ(16,385)
385   FORMAT(/)
390 CONTINUE
    READ(16,395)YL
395 FORMAT(6X,F7.0)
    LEN=YL*656*1.5
397 TLAG=LEN**.8*(S+1)**.7/1900/WSL**.5
    CLOSE(UNIT=16)
    TOTAL=TOTAL/640
    RETURN
    END
************************************************************
******    METHOD FOR COMBINING DATA FOR ANY NUMBER OF   *****
```

```
*********        SUB-BASINS FOR THE WATERSHED        ********
************************************************************
      SUBROUTINE COMB(FILE1,FILE2)
      REAL C(50,2),D(100,2),AREA
      INTEGER K,J,I,NSUB,OVER,SOIL,CHO
      CHARACTER*30 FILE,FILE1,FILE2
  401 DO 402 I=1,50
       C(I,1)=0
       C(I,2)=0
  402 CONTINUE
      DO 403 I=1,100
       D(I,1)=0
       D(I,2)=0
  403 CONTINUE
      I=1
      WRITE(*,405)
  405 FORMAT(//2X,'HOW MANY SUB-BASINS DO YOU WANT TO',/1X
     $' COMBINE?')
      READ(*,*)NSUB
      DO 440 K=1,NSUB
      WRITE(*,410)K
  410 FORMAT(//2X,'ENTER THE NAME OF THE CN/LAND USE'/1X,
     $' FILE REPRESENTING THE #',I1,' SUB-BASIN.')
      READ(*,'(A)')FILE
      OPEN(UNIT=41,FILE=FILE,STATUS='UNKNOWN')
      DO 415 J=1,6
      READ(41,413)
  413   FORMAT(/)
  415 CONTINUE
  416 READ(41,417,ERR=420)OVER,AREA
  417 FORMAT(4X,I2,35X,F12.2)
  418 IF(I.EQ.OVER)GOTO 419
      I=I+1
      GOTO 418
  419 C(I,1)=OVER
      C(I,2)=C(I,2)+AREA
      GOTO 416
  420 CLOSE(UNIT=41)
      I=1
      WRITE(*,422)K
  422 FORMAT(//2X,'ENTER THE NAME OF THE SOIL FILE'/1X,
     $' WHICH REPRESENTS THE #',I1,'SUB-BASIN.')
      READ(*,'(A)')FILE
      OPEN(UNIT=42,FILE=FILE,STATUS='UNKNOWN')
      DO 425 J=1,6
       READ(42,423)
  423     FORMAT(/)
  425 CONTINUE
  428 READ(42,430,ERR=440)SOIL,AREA
  430 FORMAT(4X,I2,35X,F12.2)
  431 IF(I.EQ.SOIL)GOTO 432
      I=I+1
      GOTO 431
```

```
432 D(I,1)=SOIL
    D(I,2)=D(I,2)+AREA
    GOTO 428
440 CONTINUE
    WRITE(*,450)
450 FORMAT(//2X,'TYPE THE NAME OF THE CN/LAND USE'/1X,
   $' FILE REPRESENTING THE COMBINED SUB-BASINS.')
    READ(*,'(A)')FILE1
    OPEN(UNIT=43,FILE=FILE1,STATUS='UNKNOWN')
    DO 465 J=1,6
    WRITE(43,460)
460    FORMAT(/)
465 CONTINUE
    DO 475 I=1,50
    IF(C(I,2).EQ.0)GOTO 475
    WRITE(43,470)C(I,1),C(I,2)
470 FORMAT(4X,F4.1,35X,F12.2)
475 CONTINUE
    CLOSE(UNIT=43)
    WRITE(*,480)
480 FORMAT(//2X,'TYPE THE NAME OF THE SOIL FILE WHICH'/1X,
   $' REPRESENTS THE COMBINED SUB-BASINS.')
    READ(*,'(A)')FILE2
    OPEN(UNIT=44,FILE=FILE2,STATUS='UNKNOWN')
    DO 485 J=1,6
    WRITE(44,482)
482    FORMAT(/)
485 CONTINUE
    DO 488 I=1,99
    IF(D(I,2).EQ.0)GOTO 488
    WRITE(44,486)D(I,1),D(I,2)
486 FORMAT(4X,F4.1,35X,F12.2)
488 CONTINUE
    CLOSE(UNIT=44)
    WRITE(*,490)
490 FORMAT(//2X,'DO YOU WANT TO COMBINE MORE'/1X,
   $' SUB-BASINS?'/1X,
   $'  1)YES'/1X,
   $'  2)NO')
    READ(*,*)CHO
    IF(CHO.EQ.1)GOTO 401
    RETURN
    END
```

APPENDIX B

FILES INCLUDED IN THE COW CREEK WATERSHED DATA BASE

COMBINATION FILE FOR SUB-BASIN 6(A)

Layer: [greg.mapcalc1] in mapset [lakecrk]
Title: greg.hydrosol + greg.landclas
Mask: <greg.cowcreek> in mapset <lakecrk>

Window:	north: 4010000.00	east: 674000.00
	south: 3997000.00	west: 667000.00
	res: 200.00	res: 200.00

Category		Acres	Hectares	Sq.mi
0	no data	21003.50	8500.00	32.82
21		9.88	4.00	0.02
22		494.20	200.00	0.77
23		326.17	132.00	0.51
24		227.33	92.00	0.36
32		108.72	44.00	0.17
33		49.42	20.00	0.08
34		39.54	16.00	0.06
41		29.65	12.00	0.05
42		98.84	40.00	0.15
43		98.84	40.00	0.15
	total	22486.10	9100.00	35.14

COMBINATION FILE FOR SUB-BASIN 6(B)

Layer: [greg.mapcalc1] in mapset akecrk]
Title: greg.hydrosol + greg.landclas
Mask: <greg.cowcreek> in mapset <lakecrk>

Window: north: 4010000.00 east: 674000.00
south: 3997000.00 west: 667000.00
res: 200.00 res: 200.00

Category		Acres	Hectares	Sq.mi
0	no data	21112.22	8544.00	32.99
21		79.07	32.00	0.12
22		662.23	268.00	1.03
23		128.49	52.00	0.20
24		98.84	40.00	0.15
25		59.30	24.00	0.09
32		88.96	36.00	0.14
33		19.77	8.00	0.03
34		9.88	4.00	0.02
35		19.77	8.00	0.03
42		158.14	64.00	0.25
43		49.42	20.00	0.08
	total	22486.10	9100.00	35.14

COMBINATION FILE FOR SUB-BASIN 6(C)

Layer: [greg.mapcalc1] in mapset [lakecrk]
Title: greg.hydrosol + greg.landclas
Mask: <greg.cowcreek> in mapset <lakecrk>

Window:	north: 4010000.00	east: 674000.00		
	south: 3997000.00	west: 667000.00		
	res: 200.00	res: 200.00		

Category		Acres	Hectares	Sq.mi
0	no data	21102.34	8540.00	32.97
21		197.68	80.00	0.31
22		583.16	236.00	0.91
23		39.54	16.00	0.06
24		49.42	20.00	0.08
31		9.88	4.00	0.02
32		197.68	80.00	0.31
41		39.54	16.00	0.06
42		237.22	96.00	0.37
43		19.77	8.00	0.03
44		9.88	4.00	0.02
	total	22486.10	9100.00	35.14

COMBINATION FILE FOR SUB-BASIN 6(D)

Layer: [greg.mapcalc1] in mapset [lakecrk]
Title: greg.hydrosol + greg.landclas
Mask: <greg.cowcreek> in mapset <lakecrk>

	north: 4010000.00		east: 674000.00	
Window:	south: 3997000.00		west: 667000.00	
	res: 200.00		res: 200.00	

Category		Acres	Hectares	Sq.mi
0	no data	21280.25	8612.00	33.25
21		59.30	24.00	0.09
22		237.22	96.00	0.37
23		69.19	28.00	0.11
26		108.72	44.00	0.17
31		29.65	12.00	0.05
32		49.42	20.00	0.08
36		39.54	16.00	0.06
41		19.77	8.00	0.03
42		395.36	160.00	0.62
43		9.88	4.00	0.02
46		187.80	76.00	0.29
	total	22486.10	9100.00	35.14

COMBINATION FILE FOR SUB-BASIN 6(E)

```
+----------------------------------------------------------------------+
| Layer:    [greg.mapcalc1] in mapset [lakecrk]                         |
| Title:    greg.hydrosol + greg.landclas                               |
| Mask:     <greg.cowcreek> in mapset <lakecrk>                         |
|----------------------------------------------------------------------|
|           north: 4010000.00        east:  674000.00                   |
| Window:   south: 3997000.00        west:  667000.00                   |
|           res:       200.00        res:       200.00                  |
|----------------------------------------------------------------------|
|    Category                    Acres      Hectares         Sq.mi      |
|----------------------------------------------------------------------|
|   0     no data             21438.40       8676.00         33.50      |
|  21                           494.20        200.00          0.77      |
|  22                           138.38         56.00          0.22      |
|  23                             9.88          4.00          0.02      |
|  31                            59.30         24.00          0.09      |
|  32                            19.77          8.00          0.03      |
|  35                             9.88          4.00          0.02      |
|  41                           247.10        100.00          0.39      |
|  42                            39.54         16.00          0.06      |
|  45                            29.65         12.00          0.05      |
|                           ----------    ----------    ----------      |
|          total             22486.10       9100.00         35.14      |
|                                                                      |
+----------------------------------------------------------------------+
```

COMBINATION FILE FOR SUB-BASIN 6(F)

Layer: [greg.mapcalc1] in mapset [lakecrk]
Title: greg.hydrosol + greg.landclas
Mask: <greg.cowcreek> in mapset <lakecrk>

Window:	north: 4010000.00		east: 674000.00	
	south: 3997000.00		west: 667000.00	
	res: 200.00		res: 200.00	

Category		Acres	Hectares	Sq.mi
0	no data	20845.36	8436.00	32.57
21		247.10	100.00	0.39
22		158.14	64.00	0.25
23		118.61	48.00	0.19
24		9.88	4.00	0.02
26		128.49	52.00	0.20
31		118.61	48.00	0.19
32		128.49	52.00	0.20
33		39.54	16.00	0.06
35		9.88	4.00	0.02
41		158.14	64.00	0.25
42		158.14	64.00	0.25
43		79.07	32.00	0.12
45		29.65	12.00	0.05
46		256.98	104.00	0.40
	total	22486.10	9100.00	35.14

SOIL TYPE FILE FOR SUB-BASIN 6(A)

Layer: [payne.soils] in mapset [msg]
Title: Payne County OK, Soils Map - 4 Hectare (9.88 ac.)
Mask: <greg.cowcreek> in mapset <lakecrk>

	north:	4010000.00	east:	674000.00
Window:	south:	3997000.00	west:	667000.00
	res:	200.00	res:	200.00

Category		Acres	Hectares	Sq.mi
0	no data	21003.50	8500.00	32.82
2	Coyle loam, 1	3 9.88	4.00	0.02
3	Coyle loam, 3	529.65	12.00	0.05
4	Coyle loam, 2	549.42	20.00	0.08
6	Pulaski fine s	108.72	44.00	0.17
10	Darnell-Rock o	59.30	24.00	0.09
11	Stephenville-D	365.71	148.00	0.57
21	Kirkland silt	29.65	12.00	0.05
25	Grainola-Lucien	59.30	24.00	0.09
26	Grainola-Lucie	79.07	32.00	0.12
32	Harrah-Pulaski	98.84	40.00	0.15
34	Norge loam, 3	5 9.88	4.00	0.02
35	Norge loam, 2	519.77	8.00	0.03
41	Easpur loam,	19.77	8.00	0.03
46	Renfrow silt	9.88	4.00	0.02
49	Renfrow and G	19.77	8.00	0.03
51	Stephenville	9.88	4.00	0.02
54	Stephenville	39.54	16.00	0.06
59	Konawa and Te	39.54	16.00	0.06
60	Mulhall loam,	29.65	12.00	0.05
62	Mulhall loam,	108.72	44.00	0.17
65	Grainola clay	19.77	8.00	0.03
66	Masham silty	138.38	56.00	0.22
71	Zaneis loam,	19.77	8.00	0.03
72	Zaneis-Huska	9.88	4.00	0.02
73	Dale silt loa	39.54	16.00	0.06
76	Coyle and Za	49.42	20.00	0.08
94	Doolin silt l	09.88	4.00	0.02
	total	22486.10	9100.00	35.14

SOIL TYPE FILE FOR SUB-BASIN 6(B)

```
+----------------------------------------------------------------+
| Layer:   [payne.soils] in mapset [msg]                          |
| Title:  Payne County OK, Soils Map 4 Hectare (9.88 ac.)        |
| Mask:    <greg.cowcreek> in mapset <lakecrk>                    |
|----------------------------------------------------------------|
|          north: 4010000.00        east:  674000.00             |
| Window:  south: 3997000.00        west:  667000.00             |
|          res:       200.00        res:      200.00             |
|----------------------------------------------------------------|
|    Category               Acres      Hectares       Sq.mi      |
|----------------------------------------------------------------|
|   0     no data         21112.22     8544.00        32.99      |
|   2     Coyle loam,        49.42       20.00         0.08      |
|   3     Coyle loam, 3 t    79.07       32.00         0.12      |
|   4     Coyle loam, 2      19.77        8.00         0.03      |
|   6     Pulaski fine      217.45       88.00         0.34      |
|  11     Stephenville-D    237.22       96.00         0.37      |
|  25     Grainola-Lu        69.19       28.00         0.11      |
|  26     Grainola-Lucie     69.19       28.00         0.11      |
|  32     Harrah-Pulaski     19.77        8.00         0.03      |
|  33     Norge loam, 1 t     9.88        4.00         0.02      |
|  35     Norge loam, 2 t     9.88        4.00         0.02      |
|  37     Port silt loam,     9.88        4.00         0.02      |
|  41     Easpur loam, oc    19.77        8.00         0.03      |
|  43     Pulaski fine sa     9.88        4.00         0.02      |
|  46     Renfrow silt l     19.77        8.00         0.03      |
|  47     Renfrow loam,      29.65       12.00         0.05      |
|  49     Renfrow and Gra    69.19       28.00         0.11      |
|  53     Stephenville fi     9.88        4.00         0.02      |
|  54     Stephenville f     39.54       16.00         0.06      |
|  58     Teller loam, 3      9.88        4.00         0.02      |
|  60     Mulhall loam,      69.19       28.00         0.11      |
|  61     Mulhall loam, 3    79.07       32.00         0.12      |
|  62     Mulhall loam,      88.96       36.00         0.14      |
|  65     Grainola clay      19.77        8.00         0.03      |
|  66     Masham silty       59.30       24.00         0.09      |
|  72     Zaneis-Huska        9.88        4.00         0.02      |
|  74     Coyle-Lucien c     19.77        8.00         0.03      |
|  76     Coyle and Zane     19.77        8.00         0.03      |
|  81     Huska silt loam     9.88        4.00         0.02      |
|                        ----------  ----------   ----------     |
|          total         22486.10     9100.00        35.14      |
|                                                                |
+----------------------------------------------------------------+
```

SOIL TYPE FILE FOR SUB-BASIN 6(C)

Layer: [payne.soils] in mapset [msg]
Title:Payne County OK, Soils Map - 4 Hectare (9.88 ac.)
Mask: <greg.cowcreek> in mapset <lakecrk>

	north:	4010000.00	east:	674000.00
Window:	south:	3997000.00	west:	667000.00
	res:	200.00	res:	200.00

Category		Acres	Hectares	Sq.mi
0	no data	21102.34	8540.00	32.97
3	Coyle loam, 3	98.84	40.00	0.15
4	Coyle loam, 2	29.65	12.00	0.05
6	Pulaski fine s	118.61	48.00	0.19
10	Darnell-Rock ou	9.88	4.00	0.02
11	Stephenville-D	9.88	4.00	0.02
21	Kirkland silt	59.30	24.00	0.09
25	Grainola-Lucie	59.30	24.00	0.09
26	Grainola-Luci	138.38	56.00	0.22
33	Norge loam, 1 t	9.88	4.00	0.02
34	Norge loam, 3	39.54	16.00	0.06
35	Norge loam, 2	49.42	20.00	0.08
40	Grainola-Ashpor	59.30	24.00	0.09
41	Easpur loam, o	19.77	8.00	0.03
42	Ashport silty c	9.88	4.00	0.02
43	Pulaski fine san	39.54	16.00	0.06
45	Renfrow silt lo	29.65	12.00	0.05
46	Renfrow silt l	19.77	8.00	0.03
47	Renfrow loam,	59.30	24.00	0.09
49	Renfrow and Gra	9.88	4.00	0.02
60	Mulhall loam, 3	79.07	32.00	0.12
61	Mulhall loam, 3	49.42	20.00	0.08
62	Mulhall loam, 3	29.65	12.00	0.05
66	Masham silty	128.49	52.00	0.20
70	Zaneis loam, 3 t	19.77	8.00	0.03
71	Zaneis loam, 2	39.54	16.00	0.06
72	Zaneis-Huska c	69.19	28.00	0.11
74	Coyle-Lucien c	49.42	20.00	0.08
76	Coyle and Zane	49.42	20.00	0.08
	total	22486.10	9100.00	35.14

SOIL TYPE FILE FOR SUB-BASIN 6(D)

Layer: [payne.soils] in mapset [msg]
Title: Payne County OK, Soils Map - 4 Hectare (9.88 ac.)
Mask: <greg.cowcreek> in mapset <lakecrk>

Window:	north:	4010000.00	east:	674000.00
	south:	3997000.00	west:	667000.00
	res:	200.00	res:	200.00

Category		Acres	Hectares	Sq.mi
0	no data	21280.25	8612.00	33.25
3	Coyle loam, 3	49.42	20.00	0.08
4	Coyle loam, 2 t	9.88	4.00	0.02
5	Bethany silt loa	49.42	20.00	0.08
6	Pulaski fine s	59.30	24.00	0.09
21	Kirkland silt l	79.07	32.00	0.12
25	Grainola-Lucien	9.88	4.00	0.02
26	Grainola-Lucien	59.30	24.00	0.09
33	Norge loam, 1 t	19.77	8.00	0.03
34	Norge loam, 3	9.88	4.00	0.02
35	Norge loam, 2	69.19	28.00	0.11
40	Grainola-Ashpo	88.96	36.00	0.14
41	Easpur loam, oc	9.88	4.00	0.02
47	Renfrow loam,	276.75	112.00	0.43
49	Renfrow and Gra	69.19	28.00	0.11
60	Mulhall loam,	9.88	4.00	0.02
61	Mulhall loam, 3	39.54	16.00	0.06
66	Masham silty cl	69.19	28.00	0.11
71	Zaneis loam, 2	39.54	16.00	0.06
72	Zaneis-Huska co	39.54	16.00	0.06
73	Dale silt loam,	9.88	4.00	0.02
76	Coyle and Zane	9.88	4.00	0.02
80	Renfrow-Urban la	69.19	28.00	0.11
81	Huska silt lo	39.54	16.00	0.06
88	Oil-Waste land	9.88	4.00	0.02
94	Doolin silt loam	9.88	4.00	0.02
	total	22486.10	9100.00	35.14

SOIL TYPE FILE FOR SUB-BASIN 6(E)

```
+---------------------------------------------------------------------+
| Layer:    [payne.soils] in mapset [msg]                              |
| Title:Payne County OK, Soils Map - 4 Hectare (9.88 ac.)              |
| Mask:     <greg.cowcreek> in mapset <lakecrk>                        |
|---------------------------------------------------------------------|
|           north: 4010000.00        east:  674000.00                  |
| Window:   south: 3997000.00        west:  667000.00                  |
|           res:        200.00       res:       200.00                 |
|---------------------------------------------------------------------|
|    Category                Acres      Hectares        Sq.mi          |
|---------------------------------------------------------------------|
|    0     no data         21438.40     8676.00         33.50          |
|    5     Bethany silt l     19.77        8.00          0.03          |
|    6     Pulaski fine san   88.96       36.00          0.14          |
|   21     Kirkland silt     148.26       60.00          0.23          |
|   25     Grainola-Lucie      9.88        4.00          0.02          |
|   26     Grainola-Lucien    59.30       24.00          0.09          |
|   33     Norge loam, 1     108.72       44.00          0.17          |
|   34     Norge loam, 3      29.65       12.00          0.05          |
|   35     Norge loam, 2 t   118.61       48.00          0.19          |
|   40     Grainola-Ashpor    19.77        8.00          0.03          |
|   41     Easpur loam, o    177.91       72.00          0.28          |
|   45     Renfrow silt       49.42       20.00          0.08          |
|   47     Renfrow loam, 2    69.19       28.00          0.11          |
|   61     Mulhall loam, 3    19.77        8.00          0.03          |
|   70     Zaneis loam, 3     19.77        8.00          0.03          |
|   71     Zaneis loam,       19.77        8.00          0.03          |
|   72     Zaneis-Huska co     9.88        4.00          0.02          |
|   74     Coyle-Lucien com    9.88        4.00          0.02          |
|   76     Coyle and Zane     19.77        8.00          0.03          |
|   81     Huska silt loa     49.42       20.00          0.08          |
|                          ----------  ----------    ----------        |
|          total          22486.10     9100.00         35.14          |
|                                                                     |
+---------------------------------------------------------------------+
```

SOIL TYPE FILE FOR SUB-BASIN 6(F)

Layer: [payne.soils] in mapset [msg]
Title: Payne County OK, Soils Map - 4 Hectare (9.88 ac.)
Mask: <greg.cowcreek> in mapset <lakecrk>

Window:	north:	4010000.00	east:	674000.00
	south:	3997000.00	west:	667000.00
	res:	200.00	res:	200.00

Category		Acres	Hectares	Sq.mi
0	no data	20845.36	8436.00	32.57
5	Bethany silt loa	19.77	8.00	0.03
6	Pulaski fine san	19.77	8.00	0.03
21	Kirkland silt	88.96	36.00	0.14
25	Grainola-Lucien	29.65	12.00	0.05
26	Grainola-Lucien	247.10	100.00	0.39
33	Norge loam, 1	39.54	16.00	0.06
34	Norge loam, 3 t	9.88	4.00	0.02
35	Norge loam, 2 to	49.42	20.00	0.08
40	Grainola-Ashpor	177.91	72.00	0.28
41	Easpur loam, o	59.30	24.00	0.09
42	Ashport silty	19.77	8.00	0.03
45	Renfrow silt l	29.65	12.00	0.05
46	Renfrow silt	128.49	52.00	0.20
47	Renfrow loam,	148.26	60.00	0.23
49	Renfrow and Grai	39.54	16.00	0.06
60	Mulhall loam,	39.54	16.00	0.06
61	Mulhall loam, 3	9.88	4.00	0.02
69	Zaneis loam, 1	39.54	16.00	0.06
70	Zaneis loam,	69.19	28.00	0.11
71	Zaneis loam, 2 t	9.88	4.00	0.02
72	Zaneis-Huska com	69.19	28.00	0.11
74	Coyle-Lucien co	49.42	20.00	0.08
80	Renfrow-Urban l	138.38	56.00	0.22
81	Huska silt loam	108.72	44.00	0.17
	total	22486.10	9100.00	35.14

SOIL TYPE/SLOPE DATA FILE

SOIL TYPE	SLOPE
2	2
3	4
4	3
5	1
6	0
10	20
11	5
25	3
26	8
32	5
33	2
34	4
35	4
37	0
40	4
41	0
42	1
43	1
45	2
46	4
47	4
49	5
51	4
53	2
54	4
58	4
59	55
60	4
61	4
62	4
65	4
66	15
69	2
70	4
71	4
72	4
73	5
74	4
76	4
80	3
81	2
88	3
94	1

COMBINATION/CURVE NUMBER FILE

COMBINATION	CURVE NUMBER
11	62
12	68
13	39
14	45
15	54
16	77
21	71
22	79
23	61
24	66
25	70
26	85
31	78
32	86
33	74
34	77
35	80
36	90
41	81
42	89
43	80
44	83
45	85
46	92

APPENDIX C

COMPLETE HEC-1 INPUT FILES FOR THE COW CREEK WATERSHED

COW1 INPUT FILE

```
ID THIS FILE REPRESENTS THE HY
ID WATERSHED
ID
IT     15 29OCT91     1230      150
IO      1        2
* **********
KK      1
KM Basin runoff calculation fo
BA     13
PH                       0      2.5      3.2      3.8      4.3
PH    5.0      5.9      6.8
LS      0       79        0
UD    3.5
* **********
ZZ
```

COW3 INPUT FILE

```
ID THIS FILE REPRESENTS COW CREEK WATERSHED DIVEDID INTO 3
ID SUB-BASINS
ID
ID
IT    15 31OCT91    1230     150
IO     1       2
* **********
KK     1
KM Basin runoff calculation for      1
BA   4.5
PH                       0      2.5     3.2     3.8     4.3
PH   5.0      5.9      6.8
LS     0       76        0
UD   1.8
* **********
KK     A
KM Muskingum channel routing from        1 to          2
RM     1      .32      .43
* **********
KK     2
KM Basin runoff calculation for      2
BA   4.0
PH                       0      2.5     3.2     3.8     4.3
PH   5.0      5.9      6.8
LS     0       82        0
UD   1.6
* **********
KK     2
KM Combining two hydrographs at control point          2
HC     2
* **********
KK     B
KM Muskingum channel routing from        2 to          3
RM     2      .51      .37
* **********
KK     3
KM Basin runoff calculation for      3
BA   4.2
PH                       0      2.5     3.2     3.8     4.3
PH   5.0      5.9      6.8
LS     0       79        0
UD   2.6
* **********
KK     3
KM Combining two hydrographs at control point          3
HC     2
* **********
ZZ
```

COW6 INPUT FILE

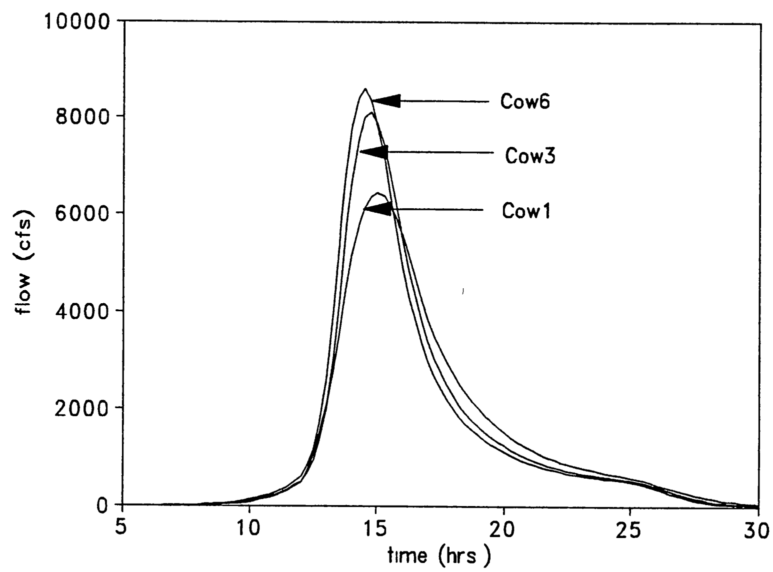
```
ID THIS FILE REPRESENTS THE WATERSHED BROKEN INTO 6
ID SUB-BASINS
ID
IT    30 26OCT91    1230     150
IO     1       2
* **********
KK     1
KM Basin runoff calculation for      1
BA   2.3
PH                        0      2.5      3.2      3.8      4.3
PH   5.0      5.9      6.8
LS     0       74        0
UD   1.6
* **********
KK     2
KM Basin runoff calculation for      2
BA   2.1
PH                        0      2.5      3.2      3.8      4.3
PH   5.0      5.9      6.8
LS     0       77        0
UD   1.8
* **********
KK     2
KM Combining two hydrographs at control point        1
HC     2
* **********
KK     A
KM Muskingum channel routing from       1 to         2
RM     1      .32      .43
* **********
KK     3
KM Basin runoff calculation for      3
BA   2.2
PH                        0      2.5      3.2      3.8      4.3
PH   5.0      5.9      6.8
LS     0       80        0
UD   1.6
* **********
KK     3
KM Combining two hydrographs at control point        2
HC     2
* **********
KK     4
KM Basin runoff calculation for      4
BA   1.9
PH                        0      2.5      3.2      3.8      4.3
PH   5.0      5.9      6.8
LS     0       84        0
UD   1.3
* **********
```

```
KK      4
KM Combining two hydrographs at control point        2
HC      2
* **********
KK      B
KM Muskingum channel routing from        2 to        3
RM      2     .51     .37
* **********
KK      5
KM Basin runoff calculation for      5
BA   1.6
PH                      0     2.5     3.2     3.8     4.3
PH   5.0     5.9     6.8
LS     0      76       0
UD   2.6
* **********
KK      5
KM Combining two hydrographs at control point        3
HC      2
* **********
KK      6
KM Basin runoff calculation for      6
BA   2.6
PH                      0     2.5     3.2     3.8     4.3
PH   5.0     5.9     6.8
LS     0      81       0
UD   2.0
* **********
KK      6
KM Combining two hydrographs at control point        3
HC      2
* **********
ZZ
```

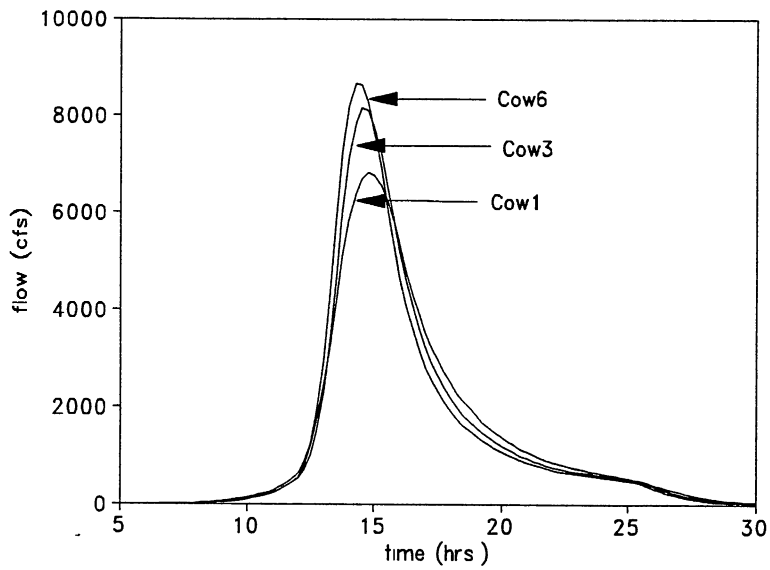
APPENDIX D

GRAPHS RESULTING FROM THE SENSITIVITY ANALYSIS

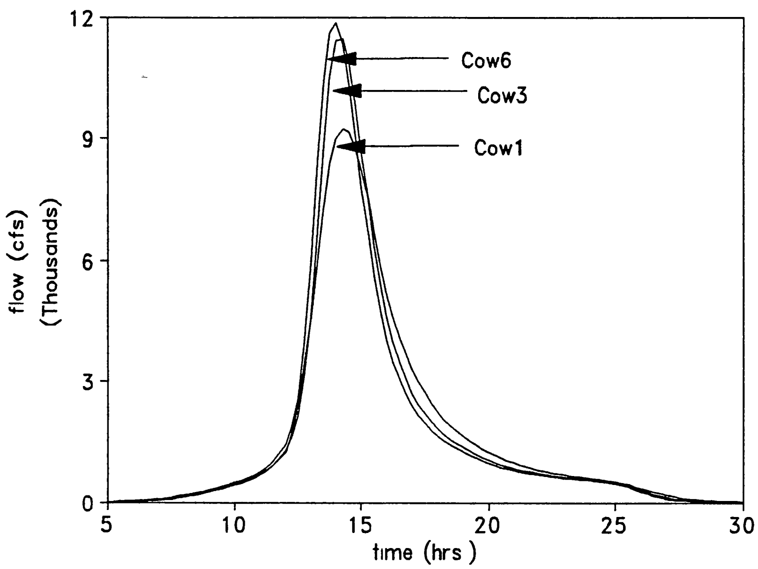
HYDROGRAPHS RESULTING FROM n +10%



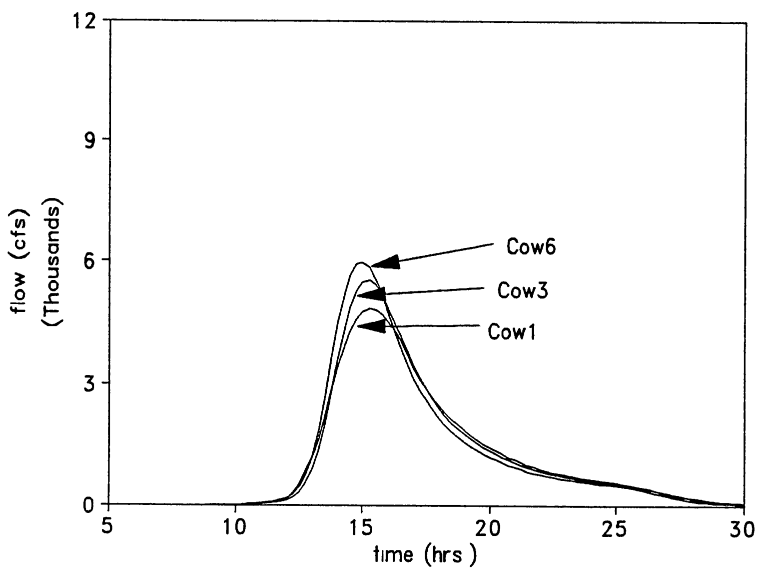
HYDROGRAPHS RESULTING FROM n -10%



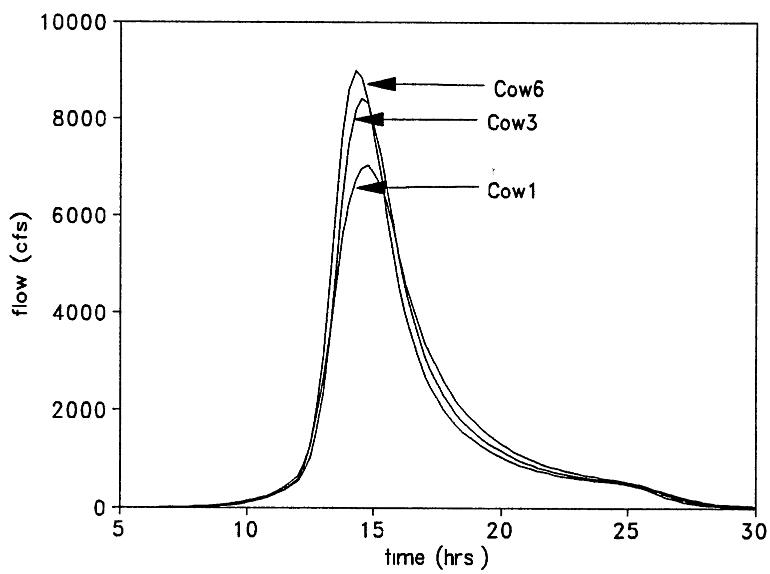
HYDROGRAPHS RESULTING FROM CURVE NUMBER +10%



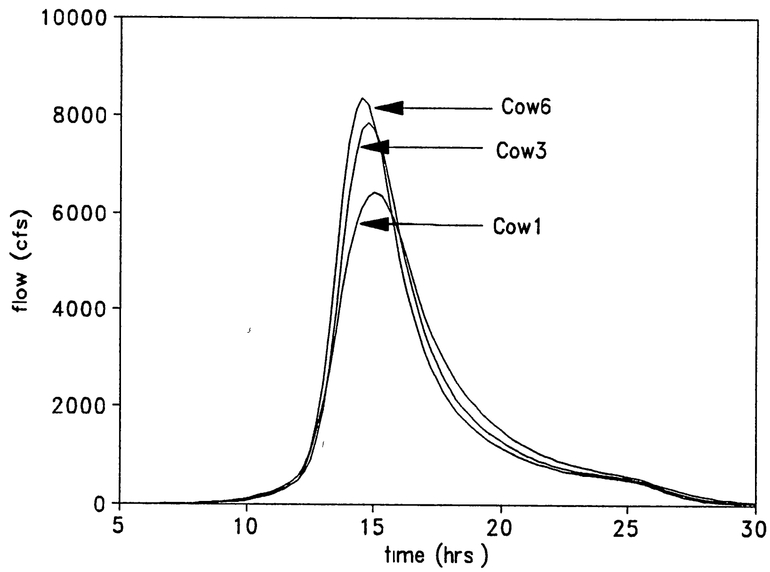
HYDROGRAPHS RESULTING FROM CURVE NUMBER -10%



HYDROGRAPHS RESULTING FROM LAND SLOPE +10%



HYDROGRAPHS RESULTING FROM LAND SLOPE -10%



VITA

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