Chapter One. Introduction

A hydrologic simulation model is, in general, composed of three basic elements, which are (1) equations that govern the hydrologic processes, (2) maps that define the study area and (3) database tables that numerically describe the study area and model parameters. When a model is constructed using a procedural programming language, such as FORTRAN, these three elements are usually processed separately and then assembled at runtime to form a model. Because of this separation, the modification on a model map will not automatically update its related databases and programs. Therefore, each time the model study area is changed or additional data are obtained, the procedure and efforts of the data collection and preparation used to construct the original model are repeated to construct a new model. The situation can be improved if all three elements of a simulation model can be integrated and if standard map bases can be built for extensive regions.

On the other hand, when looking back into the history of the numerical modeling in the area of water resources, it can be seen that the general trend of the modeling approach is moving from the periods of (1) 'function-centric' where numerical models were self-contained and supported by their own data sets, through (2) 'data-centric', where models were supported by some general database management systems, and towards (3) 'map-centric' where models would be supported by or written in GIS.

The purpose of this research is to develop a map-based flow simulation model with all of its three components integrated. In doing so, this research attempts to move towards the goal of constructing a 'map-centric' modeling approach. The map-based model is based on the concepts of object-oriented programming (OOP) and is built using a geographic information system (GIS).

The maps and databases are integrated using GIS data management tools while the data sets and programs are integrated by applying the concepts of OOP. To demonstrate how these three elements are integrated and how an integrated model can be applied to simulate hydrologic/hydraulic processes, two map-based flow simulation models, one for surface flow and one for groundwater flow are constructed using ArcView GIS as the host environment. These two models are then connected through data tables to simulate the interactions between surface and subsurface water flows. ArcView is selected as the host environment for the models because it provides both spatial database management and object-oriented programming capabilities. The remainder of this section is used to provide a brief review on the history of GIS applications in hydrologic modeling and a discussion of the GIS-related problems to be solved in this research.

A geographic information system (GIS) is designed to visualize, store and analyze the information about the locations, topology, and attributes of spatial features. In most GIS programs, data are stored and managed in a relational database embedded in the system. A GIS program can perform regular database management tasks in addition to its spatial analysis capabilities. For this reason, GIS can be considered as a relational database management system with a map interface for data presentation. In GIS, locational data and their map representations are dynamically linked so that any changes made in the databases are reflected immediately on its map presentation. The linkage between the map and databases makes GIS an ideal and strong tool for spatial data visualization and analysis.

On the other hand, hydrologic or hydraulic models are designed to simulate the processes of surface or subsurface water flow. Because the flow processes are spatially distributed, a great amount of spatially related physical data needs to be prepared and analyzed in order to construct a simulation model.

As model data processing is a tedious procedure, it is desirable to use GIS to accelerate the data preparation process. For this reason, ever since the beginning of GIS development about 16 years ago, many attempts have been made to introduce GIS into the hydrologic and hydraulic modeling process. As a result of these efforts, ARC/INFO has been linked to some hydrologic/hydraulic models such as the Hydrologic Engineering Center's HEC1 (Warwick, 1994) and HEC2 (Djokic, 1994) models, to river basin models (Grayman, 1991), to groundwater models such as MODFLOW (Watkins, 1996, McKinney, 1996), and other subsurface flow and transport models (Leipnik, 1993). More examples of this type of GIS applications can found in various publications (Kuo, 1993), but generally, this type of model-coupling has not been easy to accomplish, even though the model-coupling can be done.

Although it is generally agreed that when used properly, GIS makes a good pre-processor and post-processor for hydrologic/hydraulic simulation models, there are still problems to be solved and techniques to be improved in order to have a better integration of GIS with the hydrologic and hydraulic modeling. Listed below are the areas that will be discussed in this dissertation.

- **Developing a Simulation Model with Its Three Elements Integrated**

Although using GIS as a hydrologic/hydraulic model's pre-processor and post-processor has the benefits of reducing the amount of data preparation work, enhancing spatial data display and revealing some hidden spatial relations, the effort and cost of developing a GIS interface can also be significant and sometimes, outweigh the benefits of using it (DeVantier, 1993). One of the reasons for this high development cost is that both GIS databases and simulation models are usually self-contained and have different data structures. As a result

of this difference, a great number of programs and procedures need to be constructed simply for data conversion purposes.

This problem can be mitigated if a simulation model is constructed with all three of its elements integrated, because in such a model, the programs and maps would share the same databases and the problems of data inconsistency would be eliminated.

High set-up and operating cost can also be improved if a GIS interface developed for one model can be shared by other models. This study also attempts to develop a GIS-based system that provides a digital description of the environment to which models can be attached (Maidment, 1993). This system is used for the following three purposes: (1) as a spatial data storage and management system, (2) as a driver to feed different models with different types of data, and (3) to run these models. This type of system enables the data sharing so that a database developed for one model can be used for another. For example, data sets constructed for a rainfall-runoff model can be shared by a groundwater simulation model, a data set prepared for a for long term soil-water balance computations can be used for short term storm-flood simulation model, and so on.

• Constructing a Groundwater Simulation Model under GIS

Because most groundwater simulation models are self-contained and require a specific input data format, it is not easy to integrate an external groundwater model with a GIS. However, because GIS has the ability to manage and display spatially-referenced data, it is desirable to use GIS to support groundwater simulation models. To achieve this goal, a map-based groundwater model is constructed within the GIS environment using the concepts of spatial database management and OOP. The user interface and data processing capability

of this map-based model are enhanced by the spatial data display and analysis capabilities of the GIS.

- **Connecting the Spatially-Referenced Time-Series Data with GIS**

Because most hydrologic processes are time dependent, spatially-referenced time-series data are frequently encountered in simulating hydrologic events. Therefore, it is important to have an efficient data structure and data management system to handle spatially-referenced time-series data. Data structures designed during this research can be either embedded in or connected to a GIS map to manage the spatially-referenced time-series data efficiently and effectively.

- **Enhancing the Ability of GIS to Perform Feature-Oriented Map Operations**

Another focus of this research is the feature-oriented map operations. Feature-oriented operations refer to the spatial operations applied to a given map feature that may also involve the features of other maps (coverages). A collection of programs were designed that allow feature-oriented map operations to be performed on multiple GIS maps. A feature can be a line in an arc coverage, a point in a point coverage, or a polygon in a polygon coverage.

In GIS, spatial objects are grouped according to their feature types into thematic layers. Objects grouped into the same layer form an individual entity called a coverage. As a result of this grouping, inter-layer object operations cannot be performed efficiently in GIS. However, in order to design a hydrologic model within GIS or to make GIS work efficiently with an external hydrologic

model, one has to be able to select objects of one layer based on the attributes of the objects in other layers. Methods are designed in this study to allow more efficient feature-oriented map operations for this purpose.

In the following chapters, the problems listed above are addressed and studied. The major goal of this study is to construct map-based simulation models (with all three of their components integrated) using the concepts of object-oriented programming, relational database management, and GIS.

Chapter Two (1) provides a brief review of the development of object-oriented programming, (2) introduces the concept of a map-based simulation model and the theories from which this concept originates, (3) reviews the governing equations of some hydrologic/hydraulic processes related to the model construction, and (4) describes the relationships between the programs, map-features and databases.

In Chapter Three, the concepts discussed in Chapter Two are used to develop a map-based surface water flow simulation model. In the process of model construction, problems relating to the treatment of spatially-referenced time-series data, feature-oriented map operation, and dynamic segmentation are analyzed and solved. Other commonly encountered problems such as model calibration, model post-processing, and model modification are also addressed in Chapter Three.

In Chapter Four, the concept of map-based modeling is used to develop a map-based groundwater simulation model. To design such a model, the concepts of object-oriented programming and relational databases are applied so that the model procedures are consistent with the structure of spatial databases and model maps. The map-based model simulates the groundwater flow by alternately applying the continuity equation to the polygon features and momentum equation (Darcy's Law) to the boundary lines of the polygon features.

In Chapter Five, the map-based surface and subsurface flow simulation models are merged to simulate the interaction of surface and subsurface water flows. Notable issues be discussed regarding the integration of these two models are (1) the construction of modeling objects for surface and subsurface flows, (2) the treatment of deep and shallow aquifers, (3) the methods used for data exchange, and (4) modeling procedures over time and spatial domains.

In Chapter Six, the summary and conclusions of this research are provided, in which the technique developed and knowledge acquired from this research are described and evaluated together with some comments regarding possible future research in the area.