King Fahd University of Petroleum & Minerals

City & Regional Planning Department

Introduction to Geographic Information Systems

CRP 514 - Term 112

GIS Applications in Water Resources Engineering

(Final Report of Term Paper)

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Abstract

This paper provides a relevant background on geographic information systems (GIS), which is useful in understanding its advanced applications in water resources engineering. Some important applications of GIS in water resources are presented such as surface-water hydrology, groundwater hydrology, and water quality. Benefits of using GIS in water resources engineering are discussed.

GIS has changed the communication of water resources data by increasing their availability in the form of maps generated efficiency by cartographic tools available within many GIS software. It has also provided tools for new ways to visualize the movement of water through landscapes using dynamic visualization in three-dimensional space.

Overall, using GIS by hydrologists have provided them with powerful information and helped them in understanding its applications in water resources engineering.

List of Tables

List of Figures

Table of Contents

1. Introduction

Geographic information systems are strongly impacting the fields of water resources engineering, environmental science, and related disciplines. GIS tools for spatial data management and analysis are now considered state of the art, and application of these tools can lead to improved analyses and designs. Familiarity with this burgeoning technology may be a prerequisite for success in our efforts to create reliable infrastructure and sustain our environment *(Johnson, 2009)*.

GIS provides an integrating data and modeling environment for the conduct of these activities. A GIS provides a means to collect and archive data on the environment. Measurement of location, distance, flow various devices are typically handled in digital formats and quickly integrated into spatial database. Data processing and modeling activities can draw on these data using the GIS, and analysis results can be archived as well. The GIS spatial and attribute database can then be used to generate reports and maps, often interactively, to support decision making on which design alternatives are best and the impacts of these. Further, maps are a powerful communication medium; thus this information can be presented in public forums so that citizens concerned with planning and design choices can better understand and more involved *(Johnson, 2009)*.

Planning and design in water resources engineering typically involve the use of maps at various scale and the development of documents in map formats. For example, in a river basin study, the map scale often covers a portion of state and includes several counties and other jurisdictions. The river drains a certain geography having topographic, geologic (including types of soil), vegetative, and hydrologic characteristics. Cities and human-built facilities are located along the river and across the basin, and transportation and pipeline network link these together. All of these data sets must be established in a common reference framework so that overlays of themes can be made and coincidence of features can be identified in the planning and design phase.

The GIS is applied is manage all of these data. It provides a comprehensive means for handling the data that could not be accomplished manually. The large amount of data involved requires a GIS, as there may be many thousands of features having a location, associated attributes, and relationships with other features. The GIS provides a means of capturing and archiving these data, and of browsing and reviewing the data in color-coded map formats. This data-review capability supports quality control, as errors can be more readily identified. Also, through visualization, the user can again a better understanding of patterns and trends in data in a manner not possible if the data were only in tabular format. The GIS provides an analysis capacity as well. The database can be accessed by computer software and used as input to various modeling procedures to generate derived products *(Chin, 2006)*.

In a river basin there are many applications of GIS, for example:

- Defining the watershed and its hydrologic and hydraulic characteristics so that models of rainfall-runoff process can be applied to examine the impacts of land-use changes.
- Mapping land-use and population demographic in support of water and wastewater demand estimation procedures.
- Interpolating groundwater contaminate concentration given sampled data at observation wells spaced throughout an aquifer, or estimating snowpack amounts at un-gauged locations based on data obtained at gauged locations guided by factors of elevation and exposure.
- Managing public infrastructure, such as scheduling maintenance on a sewage collection system, notifying residents of water-pipe rehabilitation work, or identifying areas of potential low pressure during fire-response planning scenarios.
- Finding the coincidence of factors, such as erosion-prone areas having a certain combination of soil type, land, cover, and slop.

- Monitoring the occurrence and intensities of severe thunderstorm and providing tools for warning threatened population of impending hazardous flood condition.
- Providing the logical network structure for coordinating simulation and optimization models that schedule the interaction between basin water supplies, reservoirs, diversions, and demands.

In addition to the physical scope of engineering planning and design activities, the organizational context within which GIS exists is important. Whether it is a large federal agency seeking to establish water supplies for a region or a small municipality trying to keep up with rapid development, the GIS requires the establishment of procedures and standards. Often, the GIS will require a change in the way an agency's work is done. Advances in data collection and engineering measurement technologies, changes in data formats and report-generation capabilities, and requirements for data sharing across jurisdiction can be different from established historical practices. All of these factors can lead to improved practice, but they can cause stress by requiring training and change *(Chin, 2006)*.

2. Objectives

Geographic information system (GIS) concepts and technologies are being used extensively in water resources engineering planning and design, and are changing the way these activities are conducted. We are in an age when natural resources are increasingly scarce and the effects of human activity are pervasive. In this situation, the best tools available must be used to characterize the environment, predict impacts, and develop plans to minimize impacts and enhance sustainability. GIS technologies, tools, and procedures have substantial benefits for resource inventories, modeling, and choice communication to involved agencies and citizens.

Therefore, and depending on this information, I am interested to know how GIS can be used in water resources engineering and to make a general overview how it has been used to support water resources development.

3. Limitations

Actually, there are some limitations and obstacles faced me when preparing this term paper such as:

1- Applications of GIS in water resources engineering are relatively new (since 90s), and they are still being studied by scientists. Therefore, different scientists have various views on GIS applications in water resources.

2-Of course, published papers are not accessible, a searcher has to pay money to get the papers.

3- I faced some difficulties of understanding some GIS applications and technical terms cause of my recent knowledge of GIS.

4. Literature Review

Here are some literature reviews for the major sources:

1-Wolfgand-Albert Flugel, 1997, GIS with regional hydrological modeling using hydrological response units (HRUs).

Dr. Albert Flugel has performed an applications and delineation of hydrological response units (HRUs) in Germany-Brol catchment. HRU are usually the heterogeneous hydrological characteristics of drainage basin such as recharge, runoff, precipitation, topography, and land-use….etc. This study indicated that GIS method used for their delineation is applicable in basins of different climate and topography, which was usually a problem for hydrologists.

2- David R. Maidment, 1993, Developing a spatially distributed unit hydrograph by using GIS.

The goal of this paper was to develop a spatial unit hydrograph that helps scientists to determine internal distribution flow through watershed. Additional benefit was describing the connectivity of the links in the watershed network. The researcher divided watershed into a grid of elevation using GIS. Each square in the grid will allow water to flow to one of the eight near squares which has lowest elevation.

3- F. De Smedt, L. Yongbo and S. Gebremeskel, 2000, Hydrology modeling on a catchment scales using GIS and remote sensed land use information.

This research presents a physically based distributed hydrological model that uses detailed basin characteristics to predict hydrological processes. The researchers focused on the simulation of runoff. The model is validated for a small watershed by comparing calculated and observed hourly discharge for a 6 months period. The utility of the model is demonstrated by forecasting peak discharges resulting from an observed 100 years precipitation series. Actually, their calculation was amazing, the resulting calculated hydrograph compared favorably with measurements, without any need to model optimization.

4- Source: David L. Jordan, An introduction to GIS applications in hydrology.

In this article, the writer showed that why GIS is important tool in hydrology. The researcher implied that to make a sound management decisions, the effects of land cover, vegetation, soil type, topography, water quality, and other factors must be considered. GIS is the tool for combining, using and analyzing these factors.

5. GIS for Surface-Water Hydrology

5.1 Overview

A variety of data are required for surface-water hydrologic studies and modeling. Table 5.1 lists categories and types of data. Hydrologic and watershed data can be originated from a multitude of government agencies and can also be collected and processed into standardized formats. Often, the data are available for download from Internet Web sites. The data have various basic formats as raster, vectors, and associated alphanumeric attributes. Other data may require field collection and processing. Satellite imagery is an example of this type, as image processing is required to identify updated land-use and land-cover (LU/LC) characteristics. Field surveys may also be required to identify details on stream-channel characteristics, such as channel shape and roughness. In a number of instances, GIS functions are applied to develop the data into formats usable for surface-water hydrologic modeling; digital terrain-processing tools are an example of this. GIS database operations aid in collecting the various data sets into a coherent database supportive of hydrologic analyses and modeling *(Johnson, 2009)*. Most surface-water hydrology applications begin within raster data of the terrain due to the wide availability of Digital Elevation Model Data, DEMs (figure 5.1) and intrinsic GIS software functions to conduct digital terrain processing. Topography plays a primary role in the distribution and flux of water and energy within the natural landscape. Examples of interest include surface runoff, infiltration, evaporation, and heat change that take place at the ground atmosphere interface.

Table 5.1 Surface-Water hydrologic data.

Terrain	Digital elevation models Slop and aspect Watersheds and sub-catchments Drainage networks
Hydrography	Stream paths & network topology Channel data(e.g., shape & roughness) Lakes & wetlands Ditches & canals
Soils	Permeability Layer depth Soil textural Soil water content
Precipitation & Climate	Rain-gauge data Gauge locations & context Statistics(e.g., intensity, duration) Temperature Evaporation & transpiration Consumptive use
Stream flow records	Long term Storm runoff events Statistics(e.g., frequency, peak value)
Land use	Land uses(LU) Land cover(LC) Population Forecast land use

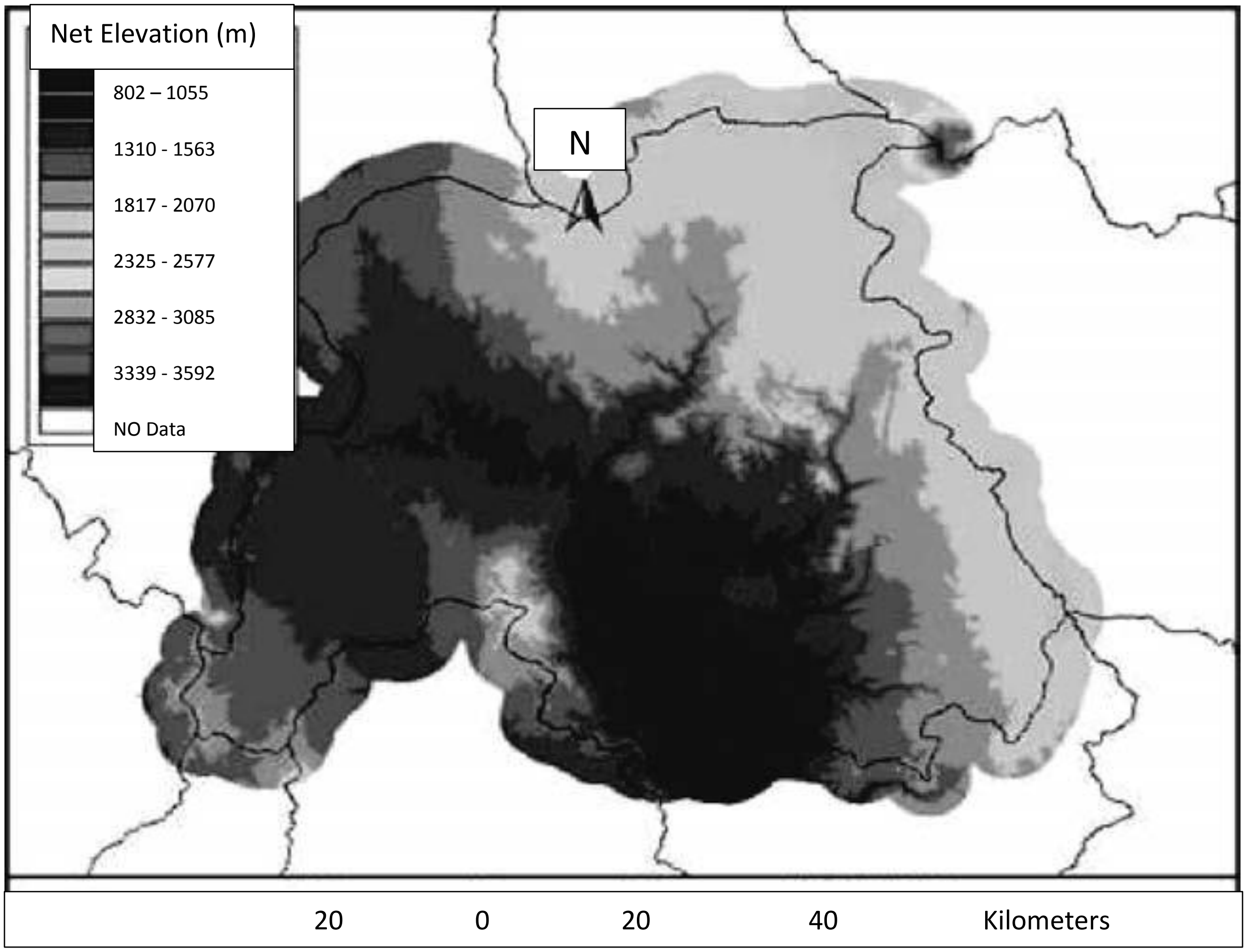

Figure 5.1 Digital elevation model data provide a preferred basis for development of a surface-water hydrology model. (*Source: http://www.nssl.noaa.gov/projects/basins/.*)

In addition, the simplicity of data management processing in the raster data model often makes raster data the first choice for hydrologic modeling *(DeBarry, 1999)*.

5.2 Floodplain Management

GIS concepts and tools are extensively applied for floodplain mapping. The objectives of this section are therefore to:

(a) Review floodplain-management concepts and information needs, including floodplain data development, hydraulics analyses, and zone definition.

(b) Consider the role of GIS in floodplain mapping and management.

GIS procedures are described for floodplain mapping of flood zones, land use, habitat, and hydrograph as well as application of GIS for determination of management-related information, such as flood damage estimation and building-permit reviews.

A primary motivation for floodplain management in the United States was the passage of the National Flood Insurance Act of 1968 *(Ackerman*, 2000*)*, which established the National Flood Insurance Program (NFIP). The NFIP is administrated by the Federal Emergency Management Agency (FEMA). The 1968 act subsidized flood insurance within communities that was willing to adopt floodplain-management programs to mitigate future flood losses.

The technical core of floodplain studies is the hydrologic and hydraulic modeling activities that lead to the delineation of the floodplain boundary. GIS has become central to the conduct of such modeling studies, providing the means for integration of the various data involved, coordinating the various models, and providing high-resolution maps required for supporting flood-management strategies *(Shamsi, 2002)*.

5.3 GIS for Surface-Water Hydrology Modeling

GIS analysis and database functions provide extensive means for developing surface-water hydrologic model data sets and modeling operations. Table 5.2 lists some of these GIS operations. A primary area of application is processing of digital terrain data to derive landscape features pertinent to hydrology such as stream paths and drainage divides. GIS database are created to help organize the multitude of spatial and non-spatial attribute data needed for surface-water hydrology studies. Intrinsic GIS surface and network analysis functions provide fundamental capabilities for driving surface-water modeling products. Examples of GIS analysis and database functions are described in this section *(Johnson, 2009)*.

Table 5.2 GIS operations supportive of surface-water modeling

Data development	*Digital terrain modeling *Slop & aspect; flow direction *Area & flow accumulation *Stream paths & drainage network *Watershed & sub-catchments
Data management	*Database of spatial data keyed to location & depth *Collation of watershed attribute data on areas & slops *Automatic formulation of model input data *Visualization of input data for error checking & consistency

The Arc Hydro tools are utilities based on the Arc Hydro data model for performing many of the aforementioned tasks of deriving hydrology data and many of them populate the attributes tools provide of Arc Hydro features. Arc Hydro provides a basic functionality that can be expanded by adding database structures and tools for a wide variety of applications in hydrology and water resources. Hydrologic models can be generally categorized in terms of how they deal with time, randomness, and the level of spatial detail. Distinctions include

(a) Event or continuous.

(b) Lumped or distribute.

(c) Empirical (system theoretic) or conceptual.

(d) Deterministic or stochastic.

(e) Measured or fitted parameter.

An event model simulates a single storm. The duration of the storm may range from a few hours to a few days. A continuous model simulates a long period, predicting watershed response both during and between precipitation events. A distributed model is one in which the spatial (geographic) variation of characteristics and process are considered explicitly, while in a lumped model these spatial variations are averaged or ignored. An empirical model is built upon observation of input and output, without seeking to represent explicitly the process of conversion (e.g.: unit hydrograph). A stochastic describes the random variation and incorporates the description in the predictions of output; a deterministic model assumes that all input, parameters, and processes are free of random variation and know with certainty. Stochastic models are increasingly being used to characterize the uncertainty bounds of model outputs. A measured-parameters model involves the direct measurement of parameters. A fitted-parameters mode, on the other hand, includes parameters that cannot be measured.

Instead, the parameters must be found by fitting the model with observed values of the input and the output *(HEC, 2000)*.

The basic processes of a hydrologic model include the following *(Vieux, 2004)*:

- Precipitation
- Abstractions and infiltration losses, soil-moisture accounting
- Overland flow generation and routing
- Stream channel routing hydraulics

5.3.1 Arc Hydro Data Model and Tools

Arc Hydro is an ArcGIS-based system developed by the Center for Research in Water Resources (CRWR) of the University of Texas at Austin *(Maidment 2002b)*.The Arc Hydro data model provides a template for the creation and manipulation of a wide variety of hydrologic-and water-resources-related objects and their associated attributes, including the appropriate rules governing their topological interaction. Of interest here are the Arc Hydro tools.

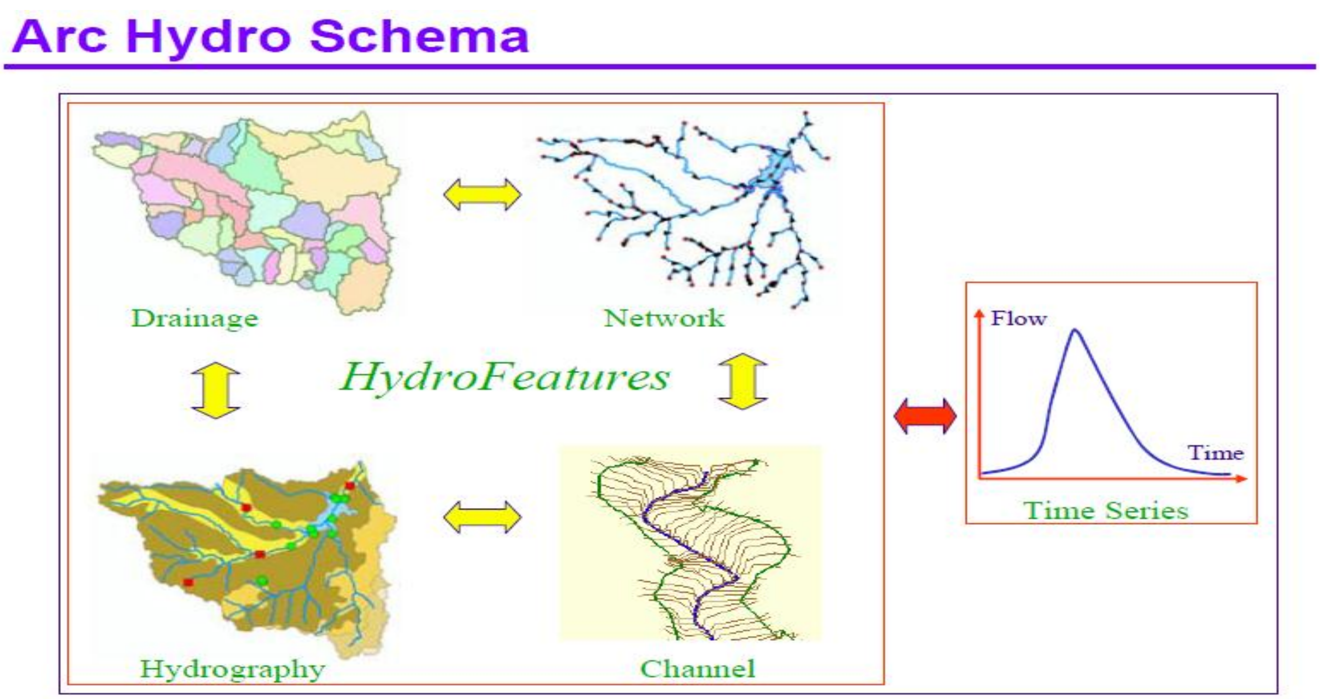

Figure 5.2 Arc Hydro data model *(Source: Maidment 2002b)*.

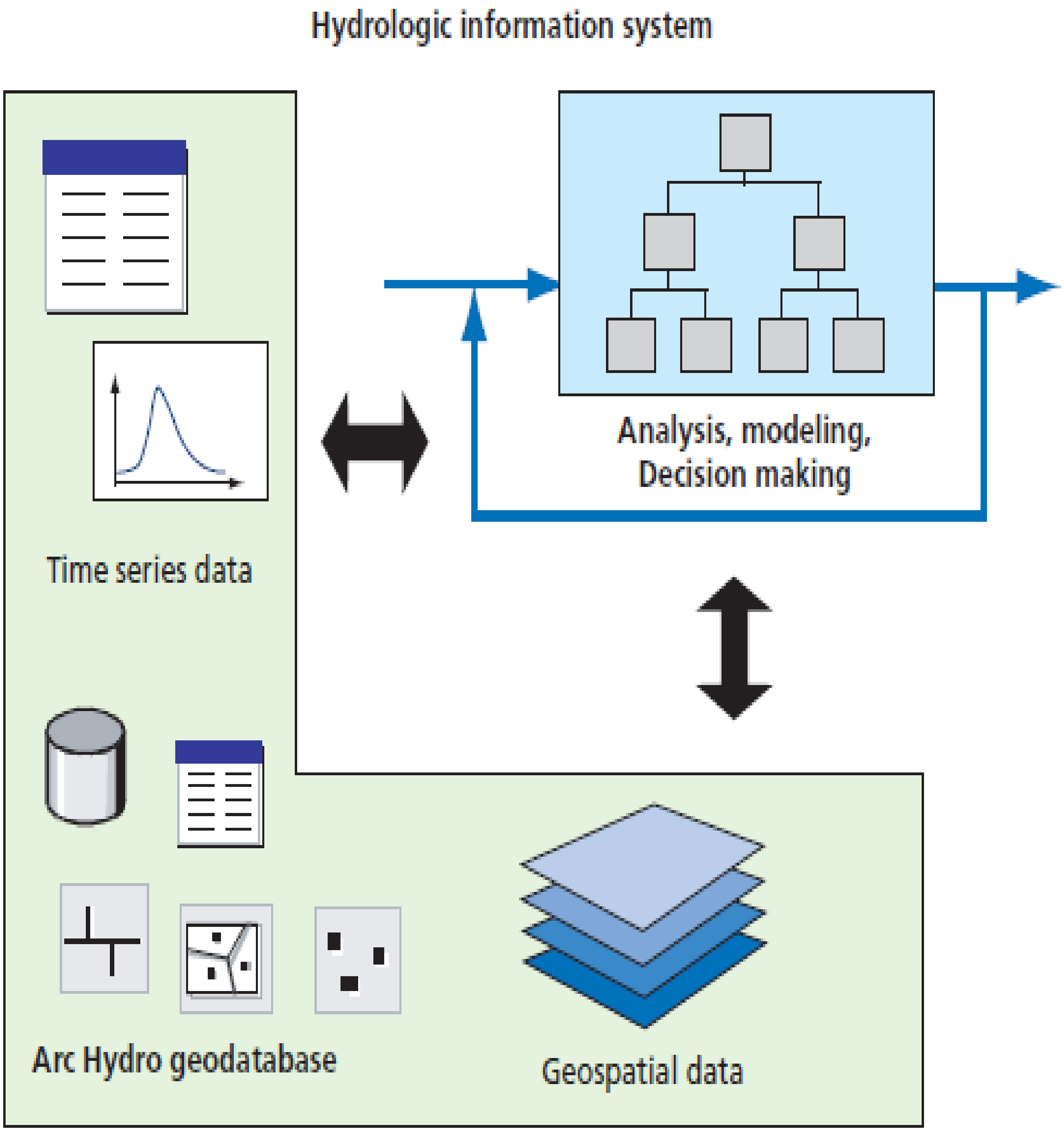

Figure 5.3 A hydrologic information system connects time series and geospatial data with hydrologic analysis and modeling *(Source: Maidment 2002b)*.

Arc Hydro provides a basin functionality that can be expanded by adding database structures and tools for a wide variety of applications in hydrology and water resources.

6. GIS for Groundwater Hydrology

6.1 Overview

Groundwater is sometimes referred to as the hidden source of water supply because it resides in the subsurface. It is of vital importance in areas where dry and extended droughts cause surface supplies to disappear. More than 1.5 billion people worldwide and more than 50% of the population of the United States rely on groundwater for their primary source of drinking water. Threats to groundwater quality have risen in importance, given the increased dependence on groundwater supplies and the long times required for clearance of contamination *(Alley etal. 2002)*.

GIS has found extensive application for groundwater assessment, as there are many types and large amounts of data involved. Proper evaluation of groundwater resources requires thorough hydrologic, geologic, and hydraulic investigations. The spatial scope may be quite local for a specific pumping well, or it may range in size from a few hundred hectares to entire basins and even countries. Use of simulation and management models is widespread in such studies, and GIS has become a primary technology for coordinating the data management and providing the interface for groundwater model development *(Bear, 1979)*.

6.2 Groundwater Hydrology and Management

Groundwater availability in any location is quite site specific, given the combination of natural hydrologic and geologic conditions as well as the human-induced changes that might exist. Quantitative methods have been developed for characterizing groundwater flows and quality, and these provide an acceptable basis for management decision. However, these methods require adequate data pertaining to hydro-geologic conditions, and these data are notoriously difficult to obtain. Thus, GIS data-management and analysis procedures help considerably in groundwater management practice *(Fetter, 1994)*.

6.3 Groundwater Data

The foundation of a usable groundwater model is the availability of high-quality data. GISs typically are an integral part of the database system to assist in organizing, storing, and displaying the substantial array of needed information. Principle types of data are commonly required. Some, such as precipitation data, are generally available and relatively easy to obtain at the time of a hydrologic analysis. Other data and information, such as geologic and hydro-geologic maps, are difficult and expensive to obtain and can require years to develop. Still other data, such as history of water levels in different parts of an aquifer system, require foresight in order to measurements over time, if they are to be available at all *(Johnson, 2009)*.

6.4 GIS for Groundwater Modeling

As listed in Table 5.2, groundwater models require a number of disparate and large data sets that are difficult to manage. GIS can help with the modeling process by coordinating data collection, providing comprehensive database operations, supporting systematic model parameter assignment, conducting spatial analysis (e.g. spatial statistics) functions, and displaying model results in understandable color-map formats. Table 6.1 also lists a variety of these GIS operations supportive of groundwater modeling *(Johnson, 2009)*.

Table 6.1 Operations supportive of groundwater modeling

Data management	*Database of spatial data keyed to location and depth. *Capture of archived site inventory data and conversion to GIS formats. *Collation of aquifer attributes data on hydro-geology factors, hydrology, and quality. *Design of FD(finite difference) model grids or FE(finite element) mesh *Automatic formulation of model input data *Visualization of input data for error checking & consistency *Statistical interpolation to assign field data to aquifer extent.
Groundwater system modeling	*Establishment of aquifer model boundary conditions *Systematic assignment of model parameters. *Interactive model simulation *Sensitively analyses aided by GIS-based parameter changes.
Model output review	*Display of model outputs in color-coded map-oriented formats *Map and graphical comparisons of aquifer simulation results with field calibration data *Model-reporting and archive

7. GIS for Water Quality

One of the most important subjects in water resources is water quality assessments of river system. It covers the entire river basin and an evaluation of best management practices to minimize nonpoint source pollution. To do this, engineers have to manage for monitoring water quality continuously, which is expensive and not currently conducted. Hydrologists decided to simulate hydrologic balance and water quality parameters to help in assessment the effects of proposed changes in land use management. Hydrologists have also linked GIS hydrologic models to facilitate model execution *(Vieux, 2004)*. GIS was preferred because it can store, manipulate, and provide spatial data for a variety of display and analytical tools, and to collect and manage input into the SWAT (Soil and Water Assessment Tool) hydrologic model.

In addition, Reservoir planning and management can be undertaken by developing a map-based surface water simulation model of any watershed, which may include rivers, lakes, or both of them. There is a need for inexpensive tools that enable planners to accurately quantify the available water supply and its ability to meet the competing demands of projects. There are now some models build using GIS (Arc View) that helped to plan and simulate a model for a watershed and its reservoirs *(Asante & Maidment, 1997)*.

GIS performs a central role in support of efforts to monitor water quality changes within a body, and modeling water quality of aquatic systems. The Arc Hydro data model *(Maidment, 2002)* has been used as a guide for integration of the large variety of spatial and attributes data into a relational geo-database.

8. Conclusion

Water resources assessment and management are inherently geographical activities requiring the handling of multiple forms of spatial data. GISs and simulation models have contributed to the identification and evaluation of potential solutions to water resource problems during the past decade. There has been a steady increase in the number and variety of functions incorporated in GISs that are suited to water resource applications. GIS has also influenced the development and implementation of hydrologic models at several different levels. For example, GISs have provided tools to compute average values more efficiently and to include at least some level of spatial effects by partitioning entire watersheds into sub-watersheds in both site-specific and lumped parameter models. Similarly, geographic information technologies have played a major role in the development of distributed hydrologic process and patterns affecting the distributed and movement of water in landscapes as well as the impact of land use on water resources over the long term.

There are many advantages for using GIS in water resources engineering such as the ability to produce more quickly, repeatable, they can be used with the visualization tools commonly found in GIS to develop customized maps and tables and effective delineation of watersheds and streams. Also, the ability of modeling systems for rivers, channels, and coastal waters.

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