By: Janelle Mongelli

New Mexico State

University Geography Department

**Introduction**

Water resources management has become increasingly important in our society. The reoccurring drought throughout the history of New Mexico has had tremendous impacts on the water supply. With more people populating the region, the dependence on both surface water and groundwater to meet water supply needs has also increased. Due to human activities, extraction of both types of water supplies has made it extremely important to evaluate, monitor, analyze, and predict the sustainability and management of water.

**What is Hydrologic Modeling?**

Another name for hydrologic modeling is spatial hydrology, which is “the study of the earth’s waters and the transport of their constituents using the spatial data structures and functions of a geographic information system (Maidment, 1996 paragraph 2)”.

New technology has opened the doors for various modeling techniques that can be used to advance our understandings of water resources assessment and management. Geographic Information Systems (GIS) has become a useful tool for integrating the spatial properties of water movement through the landscape. GIS is a “fundamental set of automated ideas and concepts rooted in over 2500 years of exploration and geographic research (Dobson, 1995) and designed to provide answers to questions based on mapped data, (DeMers, 1997, p.3)”. Integrating GIS with hydrologic models is now a popular method that allows performance evaluations of multi-objective water management strategies.

In the Urban and Regional Information Systems Association (URISA) Journal, Wilson, Mitasova, and Wright (2000), review “the contribution of GIS to the generation, management, and delivery of spatially distributed data, the advent of new GIS systems tools, and the role of GIS in hydrologic models and water resource decision support systems, (p. 61)”. Water resource management requires large amounts of spatial data, and GIS allows the compilation and analysis of these spatial data. It is a key player in helping government agencies and private organizations to produce more useful tools for managing our water resources (Wilson, Mitasova, and Wright 2000). The article also includes important research needs and suggestions, such as the development of water resource decision support systems that can be used for research applications in order to meet a specific watershed management goal. In addition, Wilson, Mitasova, and Wright 2002 describe recent accomplishments made in data collection and sharing so that now many individuals, working for corporations, small business or gout agencies are able to access data.

**Integrating Hydrologic Modeling and Geographic Information Systems**

GIS provides a consistent method for watershed and stream network delineation using digital elevation models (DEM’s) of land-surface terrain. DEM’s are digital files that contain information about the landscape and its elevation using ground points from satellite information. “It is typical to use the cell-based DEM data for surface hydrologic modeling, because of both their availability and because they are generally at a scale at which such modeling is most relevant, (Demers, 2002 p. 82)”.

Spatial hydrologic models can be created for time averaged and time varying systems. The most common theme among water modeling challenges is the need for integration of different types of routines, for example, combining different types of GIS and water resources data and integrating them across spatial scales, (Maidment, 2002). To integrate GIS and hydrologic modeling is to unite geospatial data with hydrologic processes. This means getting the physical environment to communicate about how water moves on the earth’s surface within a digital analytical framework (Merwade, V. & Maidment, 2002).

As a result of many years of interest in geospatial data, the United States Army Corps of Engineer’s Hydrologic Engineering Center (HEC) has been working towards creating tools for hydrologic and hydraulic modeling. One of the first softwares developed was the Spatial Analysis Methodology (HEC-SAM) “which included a grid-cell data bank and analysis software for hydrologic and flood damage calculations, (US Army Corps of Engineers, 2000, paragraph 1)”.

The early concepts that were used in the HEC-SAM software are similar to the GIS tools used today, but technology limitations made it difficult to process information quickly. Recently, HEC has been revitalized with the help of Dr. David Maidment from the University of Texas. HEC and Dr. Maidment worked together to formulate a watershed data structure that could be linked to GIS and hydrologic modeling (US Army Corps of Engineers, 2000). The results of this work became the hydrologic GIS preprocessor, PrePro, which attempts to code streams and watersheds under the database structure of HEC Hydrologic Modeling System (HMS). Following PrePro was HEC- Geospatial Hydrologic Modeling Extension (GeoHMS) which was developed by HEC, the Environmental Systems Research Institute (ESRI) and the help of Dr. Maidment and others from the Center for Research in Water Resources in Austin, Texas (US Army Corps of Engineers, 2000). ESRI is the largest research and development organization dedicated to GIS that has created the entire ArcUser software collection. Using the HMS extension permits for ArcView and Spatial Analyst to construct a higher quantity of hydrologic modeling inputs, (US Army Corps of Engineers, n.d.).

Dr. David Maidment is also the chief researcher and author of a tool based on ESRI GIS entitled, Arc Hydro. Arc Hydro is used to model geospatial and temporal data, which is necessary for understanding and making decisions about water resources. The model runs within an Arc GIS environment and only describes natural water systems, focusing on the description of surface water hydrology and hydrography (Maidment, 2002). The framework of Arc Hydro allows the storage of all types of water data. For example, the river networks, watersheds, water bodies and monitoring information can all be collected around the framework to produce a more thorough data model. Arc Hydro includes a regionalization tool that enables researchers to concentrate more on the study area and less on the surrounding region (Maidment, Morehouse, and Grise 2002).

**Groundwater Models**

Groundwater models take into account the basic components of the hydrologic cycle along with physical properties of the aquifer and stresses to the system, including rainfall, pumping rates and groundwater movement. Groundwater models operate by calculating the rate and direction of underground water movement through aquifers and other confined spaces (State of Michigan, 2000-2005). These groundwater flow systems can also be influenced by surface water bodies so it becomes necessary to accurately calibrate and verify the model. When the model is successfully designed it can be utilized to predict the migration pathway and contaminant concentrations in groundwater (State of Michigan, 2000-2005). Some popular groundwater models include Flow2D (or Flo2D) and MODFLOW.

Flow2D is a floodplain model that calculates the steady-state groundwater flow in order to simulate the flow of water over the riverbanks during a flood (Bigstep, 2002). For example, river flood wave progression, over bank flooding, unconfined alluvial fan floods, urban flooding, rainfall/runoff, coastal flooding and mud and debris flows can be simulated (Bigstep, 2002). Flow-2D is also said to be a ‘stand alone’ groundwater model that can be used in any location where the soil structure is, for the most part, homogeneous (Braun, 1997). It is has also been called a runoff model that originated from an element of a more complex model called CASC2D, which is part of the GIS known as Geographic Resources Analysis Support System (GRASS) (Anderson & Patel, n.d.). Flow2D integrates for precipitation rate, time step, grid size and distance, and the test surface at runtime (Anderson & Patel, n.d.). The most valuable key features of this software are volume conservation and the ability to decrease a flood wave (Bigstep, 2002).

MODFLOW-2000 is the United States Geological Survey (USGS) modular three-dimensional groundwater flow model (Harbaugh, Banta, Hill, & McDonald, 2000). The modules are grouped in packages that deal with a particular hydrologic system (Scientific Software Group, 1998) which then solve 3D groundwater flow equations using a finite difference method in order to simulate ground-water flow within a wide variety of systems (Waterloo Hydrogeologic, 1993 and Scientific Software Group, 1998). Some of these systems include water supply, containment remediation, and mine dewatering. The block-centered finite-difference approach used in the model includes layers that can be simulated as confined, unconfined, or a combination of both. Flows from external stresses such as flow to wells, flow to drains, and flow through riverbeds can also be simulated (Waterloo Hydrogeologic, 1993). MODFLOW-2000 has also incorporated additional parameters such as recharge and evapotranspiration rates. In the model, the definition of a parameter indicates which variable is being classified and which cells they are being applied to (Harbaugh, Banta, Hill, & McDonald, 2000). The main objectives of MODFLOW-2000 are to encourage the understanding of groundwater modeling by making the software easily modifiable, simple to use and maintain, easy to enhance, and effortlessly executed from any computer (Scientific Software Group, 1998). MODFLOW is most appropriate in those situations where a relatively accurate understanding of the flow system is needed to make a decision.

**Surface Water Models**

Surface water models are intended to copy the mechanism of water on the surface of a landscape. They can be used to make quantitative analysis and prediction of watershed responses to precipitation, surface water runoff, flood routing, storm water quality modeling and storm hydrograph analysis. Two types of surface models discussed in this paper are the Surface Flow Simulation (SFLowSim) model used by the researchers at the University of Texas and Riverware, a more widely employed model.

Researchers at the University of Texas discuss the use of the simulation model SFLowSim as a map based surface flow simulation model. The term map-based infers that it allows you to run the program on ArcView GIS. SFlowSim was created to provide an easy accessible route to the simulation portion of the model and other related programs such as those that modify the conditions of the model and add flow check points or flow diversion points by use of graphical interfaces (Ye, Maidement, Olivera, Reed & McKinney, 2003). The SFlowSim model includes a total of 46 programs but not all of them are important for the construction of the model or for the model simulation. They are only written to speed up the spatial data processing routine. Also described in the article were the program functions, installation steps and the types of tasks to perform such as interpolating the flow rates to flow check points.

RiverWare is a generalized river basin modeling environment applicable to detailed studies of reservoir systems such as flood control, navigation, recreation, water supply, water quality, power system economics and the effects of potential water regulations (Fulp, King, & Zagona, 2004). It also takes into consideration the operation policies, enhancement and effectiveness of power, water accounting, and operational decision making in short- or long-term timeframes (Journal of the American Water Resources, Association, 2001). It provides a river basin manager tool that assist in scheduling, forecasting and planning reservoir operations. RiverWare is also an object-oriented model, meaning that it can be used in other river basins to study a specific region of interest while reflecting new features (Fulp, King, & Zagona, 2004). There are three modes of operation to RiverWare: basic simulation, rule-based simulation, and optimization (Riverside Technology, n.d.). The Upper Rio Grande Water Operations Model (URGWOM) uses Riverware to determine the loss analysis of the Rio Chama (URGWOM, 2004). Riverware has also been used by the USBR as a long-term policy and planning model, a mid-term operations model of the Colorado River, and a daily operations model for both the upper and lower Colorado regions. Currently, it is also being implemented in the Yakima and Rio Grande Basins and will soon be used in the Trukee River Basin (Fulp, King, & Zagona, 2004).

**Hydrologic Modeling Projects Using GIS**

Watershed and runoff models are very common in the world of hydrologic modeling. The Automated Geospatial Watershed Assessment (AGWA) runs two types of hydrologic models. One is the Kinematic Runoff and Erosion (Kineros) model that builds its foundation around the orientation and physical attributes of the landscape. The goal of the Kineros model is to describe the hydrologic processes of interception, infiltration, surface, runoff and erosion for a small, specific watershed (Kineros2, n.d.). It is a distributed model that utilizes one-dimensional equations to establish a decision on the flow of the channel, how much water will flood over land due to situations such as heavy precipitation and the amount of erosion that will be produced. Spatial variations such as rainfall can be easily changed to reproduce and update the model. Ultimately, this model is effective in making decisions on urban development or any other land change issue (Kineros2, n.d.).

The other model included in AGWA is the Soil and Water Assessment Tool (SWAT) model. The SWAT model was constructed to calculate the impact of land management practices in large, complex watersheds. It is a public domain model actively supported by the United States Department of Agriculture. SWAT is a continuous-time model which uses daily averages but does not simulate in depth single-event flood routing. AGWA uses this model for output variables such as precipitation, evapotranspiration rates, percolation, surface runoff, transmission loss, water yield, and sediment yield (USEPA, 2002).

AGWA decreases the time it takes to run the above models. Its purpose is to offer qualitative approximations on runoff and erosion based on landscape changes. AGWA was created to be easily accessed by researchers, managers, and scientists in order to model data and obtain results (USEPA, 2002). In operating AGWA, digital elevation models are used to display the watershed and its data layers in order to determine input parameters. Then, the models are run and imported back into AGWA where watershed changes and sensitivity can be easily identified. AGWA can conduct watershed analyses on large areas and it also can evaluate smaller areas to uncover the source of problems within a watershed (USEPA, 2002). AGWA is posted on-line and provides a free download for the extensions that run the program, the AGWA site also contains some free available data and include links to finding other data sources.

**Conclusion**

New information technology combined with the World Wide Web has produced significant improvements in hydrologic modeling. Implementing hydrologic models within a GIS framework improves our understanding of spatial processes and patterns that affect the distribution and movement of water on the landscape. It also explains and predicts what the impact of land use will be on our water supply. Researchers and scientists are now able to obtain more accurate results by using new and improved models to make the necessary water resource management decisions for a given study area.

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