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Water Resource Applications of Geographic Information Systems

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Abstract: *This study explores the numerous ways that simulation models and geographic information systems have been combined to increase our understanding of water resource assessment and management. Reviewing the role of geographic information systems in hydrologic models and water resource decision support systems, as well as their contributions to the creation, administration, and transmission of geographically distributed data and the introduction of new GIS technologies. In addition to recent achievements, this review identifies some crucial research needs. These needs are then used to pinpoint the University Consortium for Geographic Information Science's research and educational challenges and/or specific subsets of these challenges that are especially pertinent to the water resource domain. Four sets of innovations required for im- proved water resource management are noted, and areas of focus for research and education if geographic information science is to help solve water resource challenges in the future are identified.*

Introduction

Our capacity to match the supply and demand of water of the right quality to particular localities and consumers at precise times or rates practically determines our ability to sustain life. The success (i.e. sustainability) of our houses, companies, cities, farms, and recreational places depends on the efficient operation of both natural and human water delivery systems. In order to predict, manage, and modify system behaviour to support modern lifestyles and prevent shortages (droughts), surpluses (floods), and resource impairment, significant time, money, and effort have been put into learning more about the spatial and temporal patterns and characteristics of individual hydrologic processes (pollu- tion). Fundamental difficulties persist despite the fact that worries about issues like population increase, point source pollution, soil degradation, food supply, and energy may have lessened over the last years with many good trends. Other water-related issues, such as those relating to water supply, non-point source pollution, and deteriorated surface and groundwater quality, continue to be major sources of local and international concern. Understanding the fundamental physical, biological, economic, and social processes as well as how these elements interact within watersheds will be necessary for solving these water resource concerns. The National Research Council, for instance, recently recognised five changes necessary for the management of water resources (1999: 2–8):

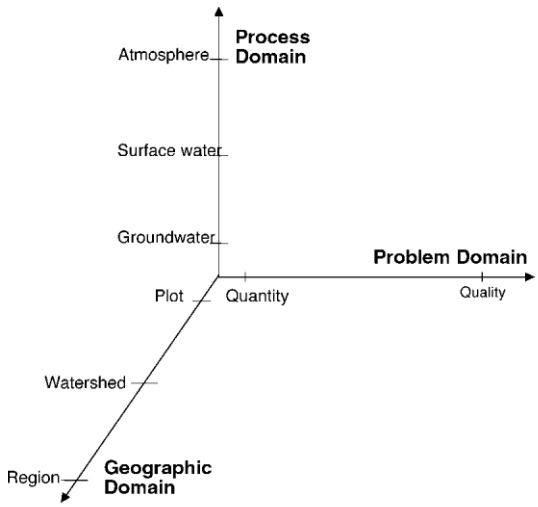
- better understanding of the connections between watershed components (such as uplands, rivers, wetlands, and groundwater);
- a better comprehension of the feedback between processes that operate at various geographic and temporal scales;
- improved accessibility to affordable, practical indicators of conditions of the watershed and quantitative techniques to assess land use and watershed management techniques;
- a growth in the number of sophisticated watershed simulation models that managers who are not scientific professionals can use; and
- a better comprehension of the roles that risk and uncertainty play in the decision-making process.

When viewed in this light, assessing and managing water resources are fundamentally geographical tasks requiring the administration of many types of spatial data. To advance our understanding in these fields, various fusions of geographic information systems (GISs) and simulation models will be necessary. While simulation models can give decision-makers interactive analysis tools for comprehending the physical system and assessing how management decisions might affect that system, GISs offer strong new tools for the gathering, storage, administration, and display of map-related information (National Research Council 1999).

GIS solutions for water resources will also need to be versatile. Interactions between the hydrosphere, atmosphere, lithosphere, and biosphere are at the heart of many of the issues. Since many of the crucial hydrologic processes have local, regional, national, and global dimensions, the solutions must accommodate conflicting groups of consumers (Naiman et al. 1997, National Research Council 1999).

Furthermore, because much of the basic hydrologic research

Figure 1. The process, problem, and geographic domains that might be used to classify water resource applications of GIS.



The immediate challenges in the water resource domain are:

- to identify ways in which GIS can facilitate more effective and/or more efficient water resource management;
- to develop GIS-based methods that address specific water resource challenges and problems; and
- to train the next generation of water resource scientists, engineers, and policy analysts to sustain the continued evolution and appropriate use of GIS-based water resource applications.

The remainder of this paper is divided into 5 sections. The first section reviews how various combinations of GISs and simulation models have been used to advance our knowledge of water resource assessment and management. The contribution of GIS to the generation, management, and delivery of spatially distributed data, the advent of new GIS tools, and role of GIS in hydrologic models and water resource decision support systems are reviewed. Some important research needs as well as recent accomplishments are identified. The next two sections describe the University Consortium for Geographic Information Science (UCGIS) individual research and education challenges and areas within these challenges that are particularly relevant to the water resource domain. The next section summarizes four sets of innovations required for improved water resource management and identifies priority areas for research and education if geographic information science (GIScience) is to help solve water resource problems in the future. The final section offers some concluding comments and highlights the most important findings and issues.

Major GIScience Contributions and TheirSignificance

GIScience has played a major role in the development of distrib- uted hydrologic models and in improving our understanding of the spatial aspects of the distribution and movement of water in landscapes. It has also greatly influenced the study of the impact of land use on water resources. The following illustrate some ways in which GIS technology has already advanced water resource management.

New GIS Data, Their Management and Delivery

The management of water resources requires a wide range of spa-tial data, from hydrography and water distribution and collec-tion systems, representing the status of water resources, tophenomena influencing the quality and movement of water suchas terrain, climate, soils, and land use.

Hydrologic and Water Quality Data. GIS has enabled govern- ment agencies and private organizations to extend the delivery of their data from numerical tables to maps and to support various forms of spatial searches for relevant data. A good example of the latter is the Environmental Protection Agency "Surf Your Water- shed" site, which allows the user to obtain water quality data in the form of maps and tables (see http://www.epa.gov/surf/ for details). Similarly, the U.S. Fish and Wildlife Service's National Wetlands Inventory provides information about wetlands (see http://www.nwi.fws.gov/ for details) and the National Weather Service's Hydrologic Information Center provides information on river and streamflow conditions, floods, droughts, etc. (see http://www.nws.noaa.gov/oh/hic/ for details). Numerous state agencies provide state or regional data, such as the Illinois Stream Information System (see http://www.gis.uiuc.edu/research/ info_systems/ISIS/isis.html for details) and the Montana Water Information System (see http://nris.state.mt.us/wis/wis1.html for details). The University of Arizona has compiled a list of approxi- mately 300 land-surface hydrology data links (see http:// www.hwr.arizona.edu/hydro_link.html for details).

These types of capabilities and data sources have an enor-mous impact beyond research and management because of their potential influence on, for example, the values of real estate or decisions on business locations. These developments also elevate the importance of metadata (i.e., information about where, when, and by whom the data were collected, its projection, datum, co- ordinate system, and accuracy). The Federal Geographic Data Committee (FGDC) (1995) has instituted a National Spatial Data Infrastructure and established a metadata standard for describ- ing the minimum set of metadata required for GIS information. These metadata are required for the clearinghouse system of data search and retrieval, in order that users may decide whether a particular data set is adequate for their particular purpose(s). Hydrologic data are part of the essential spatial data layers iden-tified by the FGDC in the framework approach to establishing a national feature-oriented database in the U.S., as more data are

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generated by local institutions than by federal agencies. The 1:100,000-scale hydrologic data set was the first framework layer to be completed for the nation.

There has also been a gradual but steady increase in the spatial content of several special-purpose hydrologic data sets. Graham et al. (1999), for example, described the development of a new data set of watersheds and river networks that can be used to route continental runoff to the appropriate coast (i.e., ocean or inland sea). This data set includes watershed and flow direction information, as well as supporting hydrologic data, at 5-minute, 1/2°, and 1° resolutions globally. This data set will be useful in fully coupled land-ocean-atmosphere models, terrestrial ecosystem models, and macroscale hydrologic modeling studies.

Digital Elevation Models. Topographic information cast in the form of digital elevation models (DEMs) has had a profound impact on water resource applications of GIS by stimulating the research and development of distributed hydrologic and non-point source pollution models and their linkage to GIS. New technologies such as IFSAR (interferometric synthetic-aperture radar), LIDAR (light detection and ranging), and real-time kinetic surveys (based on the mobile global positioning system (GPS)) are bringing higher levels of detail and vertical accuracy to terrain mapping (i.e., resolutions of 1-2 m, with 15-cm vertical accuracy). These new data sources will substantially increase our capacity to analyze and predict the movement of water and related contaminants in natural and anthropogenic landscapes. Radar technology, for example, was used in conjunction with the recent National Aeronautics and Space Administration/Department of Defense shuttle mission to obtain data for a new 30-m resolution global DEM, thereby creating the potential for hydrologic studies at the continental/global scale at a level of detail currently possible only for regional scales.

Climatic Data. The Internet has also expanded access to and extended the delivery options for national climate station data (see http://weather.ncdc.noaa.gov/ for details), and there has been a gradual but steady increase in the spatial content of special-purpose climatic data sets.

Hutchinson et al. (1996), for example, described the development and distribution of a gridded topographic and mean monthly climate database for the African continent. The monthly mean precipitation and temperature grids were prepared by applying fitted thin-plate splines to the new Africa DEM. The final surfaces interpolate monthly mean temperatures to within standard errors of about 0.5°C and monthly mean precipitation to within errors of about 10-30% (Hutchinson et al. 1996). These data are often distributed in conjunction with hydrologic and water quality data (e.g., the Montana Water Information System). The WSR-88D (NEXRAD) weather radar and some of the new satellite sensors offer spatially distributed data at a much finer spatial and temporal resolution compared to traditional climate station networks.

Soil Data. The State Soil Geographic (STATSGO) and Soil Sur- vey Geographic (SSURGO) database products provide soil infor- mation for states and counties, respectively (Bliss and Reybold 1989, Reybold and TeSelle 1989). The SSURGO database reproduces the soil mapping units portrayed at scales of 1:15,000-1:20,000 on county soil survey maps and records the attributes by soil layer or horizon for 1-3 soil series in each mapping unit. The STATSGO database portrays generalized soil mapping units and records at- tributes by soil layer for 1-21 soil series in each mapping unit. Several researchers (Foussereau et al. 1993, Maclean et al. 1993, Rogowski and Hoover 1996, Rogowski 1997) have proposed op- tions for combining these data with other data sets to predict con- tinuous changes in soil water attributes that may vary substantially across the landscape (Wilson 1999a, b). A number of new ap- proaches for predicting soil attribute values that abandon the soil survey paradigm altogether have been proposed and are discussedin the section entitled “Spatial Interpolation Tools.”

Land-cover Data. Most of the recent attempts to prepare land- cover assessments for large areas (e.g., multiple counties, states, or continents) have used meteorological satellite data. Loveland et al. (1995), for example, generated a multilevel land-cover da- tabase from the statistical analysis of multidated Advanced Very High Resolution Radiometer satellite data for the continental U.S. that serves as a prototype for a global land-cover database currently under development. Omerik (1996) also used satellite data with other digital data sources to produce an ecoregion map and database for the continental U.S. The Gap Analysis Program (Scott and Jennings 1998) used similar source data and aims to produce maps of biodiversity on a state-by-state basis (for addi- tional details on these products and their availability, see http:// www.gap.uidaho.edu/). Finally, the Digital Orthophoto Quad- rangle program of the United States Geographical Survey (USGS) aims to produce digital orthophotos for the continental U.S. at a horizontal resolution of 1 m and positional accuracy of 6 m. These photographs will help tremendously with the verification and integration of some of the other data sets and the visualization of the results of GIS-based modeling applications (for additional details, see http://nsdi.usgs.gov/nsdi/products/doq.html).

The steadily increasing availability of remote sensing data has stimulated the study of interactions between land use and water resources. New multispectral sensors and satellite platforms and archives of digital remote sensing data from the past two decades have moved this study from the spatial to the spatiotem- poral level and created the potential to better understand dy- namic landscape processes influencing water resources (e.g., the impact of deforestation and urban growth). Wilkinson (1996) recently summarized the major challenges and problems that must be overcome to more effectively use the new forms of satellite data. Gahegan and Flack (1999) showed how modern comput- ing tools might be used with these data and other GIS data themes to solve some of the identified problems.

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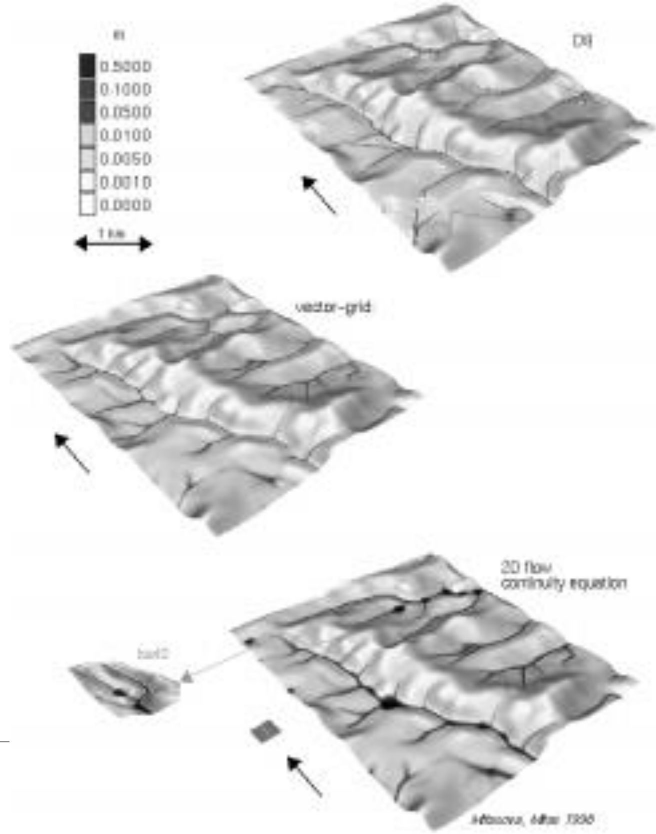
GIS Tools

There has been a steady increase in the number and variety of functions incorporated in GISs that are suited to water resource applications during the past 5-10 years. This trend is best exemplified by the GRASS GIS (2000) whose open architecture is particularly suited to the rapid prototyping of new functions in support of environmental modeling applications. Overall, four new and rapidly evolving sets of tools with strong connections to water resource applications of GIS can be identified.

Spatial Interpolation Tools. The incorporation of sophisticated methods using geostatistics (kriging) and radial basis functions (splines) has provided new tools for creating spatial and spatiotemporal models of land surfaces, climatic phenomena (e.g., precipitation and temperature), soil properties, and water quality from measured data. The inclusion of the ANUDEM (Hutchinson 1989) elevation gridding procedure in ArcInfo (Versions 7.0 and higher) illustrates these new capabilities. ANUDEM and TOPOGRID (as it is called in ArcInfo) take irregular point or contour data and create square-grid DEMs. The procedure automatically removes spurious pits within user-defined tolerances, calculates stream and ridgelines from points of locally maximum curvature on contour lines, and (most importantly) incorporates a drainage enforcement algorithm to maintain fidelity with a catchment's drainage network. The increased availability of GPS-derived elevation data (Twigg 1998) and the difficulty of using published USGS DEMs for hydrologic studies documented by Hammer et al. (1994), Zhang and Montgomery (1994), Hodgson (1995), and Mitasova et al. (1996) suggest an important role for tools such as these in the future.

Spatial interpolation tools have also been used to construct climate surfaces. Hutchinson et al. (1996), for example, used the procedures in ANUSPLIN (Hutchinson 1995a, b) to fit trivariate thin-plate spline functions based on longitude and latitude in degrees and elevation in kilometers to climate station data for Africa. Similar products have been prepared in the U.S. as well. Daly and co-workers (Daly et al. 1994, Daly and Taylor 1996) generated a series of monthly mean precipitation grids for the continental U.S. using the PRISM model, and Running and Thornton (1996) prepared daily estimates of precipitation and temperature for Montana in 1990 using the MTCLIM-3D model.

Several recent projects have analyzed the accuracy of interpolated surfaces and their parameters derived by various methods. Bolstad and Stowe (1994), for example, evaluated the accuracy of elevations, slopes, and aspects computed from two different data sources and Gao (1997) described the impact of DEM resolution on the accuracy of terrain representation and slope gradients in three distinctive study areas. Moore (1996) showed that the topographic attributes calculated as second derivatives, such as plan and profile curvature, are especially sensitive to the choice of data source and resolution. Carrara et al. (1997) defined a series of objective criteria for evaluation of the quality of digital terrain models derived from contour lines and used them to evaluate four



different interpolation procedures. Stillman (1996) compared ANUSPLIN, MTCLIM-3D, and PRISM model performance and found that all three models produced statistically similar monthly mean precipitation estimates for a moderately large study area cov- ering parts of Idaho, Montana, and Wyoming during the period 1961-90. Overall, the computer-generated climate surfaces repre- sent a major advance over their hand-drawn predecessors. They cost less and can be produced more quickly, they are repeatable, and they can be used with the visualization tools commonly found in GIS to develop customized maps and tables (Custer et al. 1996, Daly and Taylor 1996).

The shift in conceptual paradigms of soil survey and map- ping that has occurred during the past 30 years represents an- other important innovation (Burrough et al. 1997). The early models, exemplified by the STATSGO and SSURGO databases, used crisp classes in attribute space linked to crisply delineated

Figure 2. Examples of upslope contributing areas representing steady state water flow using different flow routing algorithms:

(a) D8 routing to one of the eight neighboring cells, (b) vector- grid algorithm using 360 directions (Mitasova et al. 1996), and

(c) two-dimensional flow as a solution of bivariate continuity equation. The continuity equation offers a physics-based approach that incorporates dispersal flow, filling of depressions, and flood-ing of flat areas.

mapping units in geographical space. A series of recent models has utilized fuzzy classification and geostatistical interpolation for simultaneously handling continuous variation in both attributes and location (for a description of the basic strategy, see McBratney and Odeh 1997). These methods mean that the values of soil properties obtained when a GIS is queried are increasingly likely to be estimates derived by methods of spatial interpolation, such as kriging, from actual data stored in the GIS. These changes are likely to improve both the model inputs and the ways in which uncertainty and error in model inputs and outputs are handled (Davis and Keller 1997, Lark and Bolam 1997). These concepts and the accompanying tools have been applied most often to soil attributes but are equally adept at describing other types of environmental variation (Burrough 1996b). Recent work (Bardossy and Disse 1993, Bardossy and Duckstein 1995, Mitas et al. 1996, Mitasova et al. 1996, Mitas and Mitasova 1998) illustrates the potential benefits of using these types of innovations to develop spatially distributed hydrologic models.

Watershed Delineation and Flow Tracing Tools. Numerous algorithms for the delineation of watersheds and extraction of stream networks from DEMs have been developed and implemented in GIS over the past decade (e.g., Band 1986, Costa-Cabral and Burges 1994, Mitasova et al. 1996, Tarboton 1997). These algorithms support the efficient partitioning of landscapes into hydrologic units necessary for hydrologic modeling and water resource assessment. The development of methods to calculate topographic attributes (e.g., slope, aspect, or curvature) has provided the basic parameters required for flow routing and hydrologic models (e.g., Wilson and Gallant 2000). Flow tracing has allowed the simulation of the movement of water, sediment, and other pollutants through landscapes and improved our understanding and identification of potential sources of non-point source pollution (Figure 2).

Map Algebra Tools. Map algebra tools, which are available for raster modules in many GISs, have enabled researchers to write simple water resource models for raster data (Shapiro and Westervelt 1992) as well as process the input data for more complex hydrologic models linked to GIS. Several water-quality related tools that combine existing GIS commands with map algebra operations have been developed (e.g., Mitasova et al. 1999), and writing simple models using map algebra has become an integral part of GIS courses. To better support dynamic environmental modeling, Wesseling et al. (1996) developed new tools for map algebra supporting computation with spatiotemporal data.

Computer Cartography and Visualization Tools. GIScience has changed the communication of water resource data by increasing their availability in the form of maps generated efficiently by cartographic tools available within many GISs. It has also provided tools for new ways to visualize the movement of water through landscapes using dynamic visualization in three-dimensional space. Mitas et al. (1997) used several case studies to illus-

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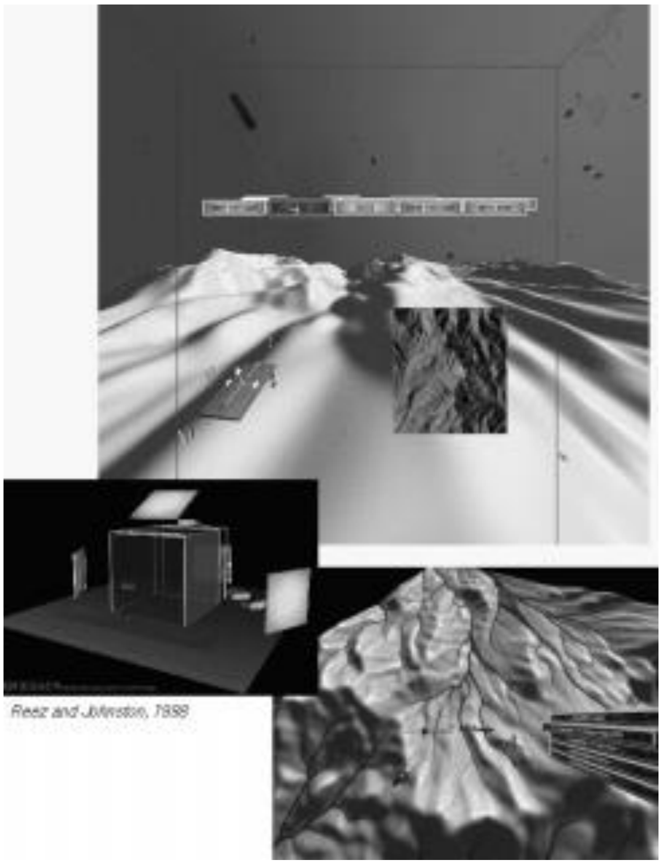
Figure 3: Visualization and interaction with terrain model and simulated water flow in virtual reality CAVE (Johnston and Reezand 1998).



trate the role of exploratory cartographic visualization in the de- velopment and presentation of models of landscape processes and patterns. Their approach integrated knowledge from GIScience, computer cartography, and scientific visualization, and supports advanced visual analysis of multivariate georeferenced data by displaying multiple surfaces and volumes in an appropriate pro- jection of 3-D space together with point and vector data. These visualizations can be implemented within World Wide Web (Web) documents as animations showing change through time. Dynamic cartographic models are now used either as a process of research and discovery with visualizations feeding refinements of models or as a method of communicating complex measured or mod- eled geographic phenomena, which is frequently encountered in water resource applications. Other examples of work of this type include Hibbard and Santek (1989), Fisher et al. (1993), Rhyne et al. (1993), Hibbard et al. (1994), and Brown et al. (1995). Another important development has involved the extension of interactive visualization capabilities to cartographic models ac- cessible through the Internet using Virtual Reality Modeling Lan- guage. Experiments are being performed with the aim of developing tools to visualize and manipulate hydrologic data and models using virtual reality in ways that will allow users to di- rectly interact with the landscape and models (in real time) (e.g., Figure 3; Johnston and Reez 1998).

Hydrologic Modeling

GIScience has influenced the development and implementation of hydrologic models at several different levels. The examples that follow are instructive because they illustrate how GIScience has been used to address water supply, water quality, and storm-water management problems in several different contexts.

Traditionally, watersheds have been represented as homogeneous units with terrain, soil, and cover conditions described by average values. GIS has provided the tools to compute these averaged values more efficiently and to include at least some level of spatial effects by partitioning entire watersheds into smaller sub-watersheds. Shamsi (1996), for example, combined a planning level GIS with the Penn State lumped-parameter Runoff Model (PSRM) and used them to implement a watershed-wide stormwater management plan. The model outputs were used to create a watershed-release rate map that satisfied the requirements of the Stormwater Management Act of Pennsylvania (1978) and provided a practical tool for implementing stormwater management plans. The adoption of this approach in six of Pennsylvania's 356 designated watersheds indicates that the integration of PSRM and GIScience offers cost-effective and technically sound solutions to Pennsylvania's watershed-wide stormwater management problems. Djokic and Maidment (1991) used ArcInfo to simulate the drainage system and assess whether the existing drainage system in a portion of the City of Asheville, North Carolina can accommodate 10- and 25-year return period design flows. Their approach used the rational method to examine contributions from surface terrain (i.e., overland flow), man-made structures (i.e., pipes and channels), and stormwater intakes.

Numerous lumped-parameter models (e.g., HEC-1, HEC2, MODFLOW, SHE, and SWAT) have been linked to GIS in these ways to predict surface- and ground-water flows. Orzol and McGrath (1992), for example, described how the structure of MODFLOW was altered to facilitate its integration with ArcInfo; they demonstrated that the results were the same as if the model was run as a stand-alone product. Similarly, Hellweger and Maidment (1999) automated a procedure to define and connect hydrologic elements in ArcInfo and ArcView and wrote the results to an ASCII file that is readable by the Hydrologic Engineering Center's Hydrologic Modeling System.

These lumped models simulate a broad spectrum of processes (e.g., surface and subsurface water flow, and sediment and pollutant transport) with continuous time simulation (e.g., SWAT - Arnold et al. 1993). The results represent averages for entire watersheds and/or sub-watersheds and often provide support for management at a regional level, which involves, for example, the identification of watersheds with high risk land uses and the designation of watershed level conservation areas. These watershed-based models have been linked to GIS for a number of years and, currently, several on-line versions are available (e.g., SWAT - Srinivasan and Arnold 1994 and L-THIA2 - Lim et al. 1999). The modular structure and availability of the GRASS GIS source code have favored its use in many of these environmental modeling applications (for additional examples, see

Vieux and Gauer 1994, Mitas et al. 1996, Vieux et al. 1996, Mitas and Mitasova 1998).

The methods used to link GIS and simulation models also vary tremendously from one application to the next. Watkins et al. (1996) compared the advantages and disadvantages of differ- ent GIS/model interfaces and showed how the spatial analysis and visualization capabilities of GIS could be used to improve parameter estimation/determination, grid design and scale effects, and the sensitivity of model outputs to parameter uncertainty and model discretization. Wilson (1999a) reviewed many of the recent attempts to develop models inside GIS and geographic modeling systems. The latter aim to provide libraries of land- scape simulation components from which watershed simulation models can be assembled to represent user-specified processes and problems in watersheds of interest (e.g., Peters 1995, Leavesley et al. 1996a, b). The accomplishments of the Danish Hydraulic Institute are particularly noteworthy in this regard. They have implemented numerous modeling systems for river basins, ur- ban drainage, sewer systems, rivers and channels, estuaries, and coastal waters during the past decade and since 1998 have em- barked on an ambitious program to link their models with the ESRI (Environmental Systems Research Institute) family of GIS products. Many of their modeling systems now support GIS data transfer and one, MIKE BASIN (which provides a versatile deci- sion support system for integrated water resources planning and management), runs inside the ArcView GIS (for additional de- tails, see http://www.dhi.dk/).

GIS has also been used to transform site-specific models into spatially distributed models. Carbone et al. (1996), for example, combined GIS and remote sensing technologies with SOYGRO (Wilkerson et al. 1983), a physiological soybean growth model, and used them to predict the spatial variability of yields in Orangeburg County, South Carolina. This model relates the major processes of soybean growth (e.g., photosynthesis, respiration, tissue synthesis, translocation of protein, and senescence) to en- vironmental conditions. The ArcInfo GIS was used to organize the meteorological, soil, and crop management inputs, and the SOYGRO model was run for 40 combinations of weather and soil conditions over a 6-year period (1986-91). The results re- vealed that the spatial variability in simulated county yield was large and linked to soil moisture availability. Carbone et al. (1996) concluded that the examination of spatial patterns of simulated yield improved county production estimates and identified vul- nerable areas during droughts.

These assessments take many different forms and have been conducted for larger areas as well as those already cited (Wilson 1999b). Corbett and Carter (1996), for example, showed how GIS can be used to: 1) synthesize and integrate more data than in the pre-GIS era, and 2) shift the design of agro-ecological and agro-climatological studies toward user-specified classifications. Their analysis focused on Zimbabwe, a semi-arid country where a national agro-ecological classification and map, the Naturalised Regions scheme (Vincent and Thomas 1960), has been widely used in agricultural research and policy-making. This map used rainfall and temperature data to predict effective rainfall and vegetation between stations. Corbett and Carter (1996) constructed seasonal rainfall surfaces for Zimbabwe using 10-day rainfall data (82-99 stations; 31 years of data), the African DEM (13,400 grid points) produced by Hutchinson et al., and the ANUSPLIN (Hutchinson 1995a, b) climate interpolation procedures. Mean rainfall and annual rainfall anomaly surfaces were generated and combined using the population surfaces of Deichmann (1994) to show that only 19% of Zimbabwe's population lives in areas that can expect to receive more than 600 mm of rainfall (i.e., the approximate threshold for maize cultivation in southern Africa) with 75% probability.

GIS is sometimes used to vary model inputs and to compare model outputs with field data in the hope of improving the scientific basis of key water quality policies and management plans. Inskeep et al. (1996), for example, compared several modeling approaches that might be applicable for classifying SSURGO soil map units according to their leaching potential. They also used detailed site-specific measurements in some of their model runs and they compared the model results with observed data collected at a field site in southwestern Montana. Data from a 2-year field study of pentafluorobenzoic acid, 2,6-difluorobenzoic acid, and dicamba (3,6-dichloro-2-methoxybenzoic acid) transport in fallow and cropped systems under two water-application levels were compared to simulations obtained using the Chemical Movement through Layered Soils (CMLS) and Leaching and Chemistry Estimation (LEACHM) models. CMLS is a one-dimensional solute transport model that uses a piston-flow approach to simulate the vertical movement of selected chemicals through the agricultural root zone on a layer-by-layer basis (Nofziger and Hornsby 1987). LEACHM is a one-dimensional finite difference model designed to simulate the movement of water and solutes through layered soils that has been validated and used as a predictive tool at the plot and field scale (Wagenet and Hutson 1989, Wagenet et al. 1993). Several attempts have been made to combine both of these models with GIS databases for regional scale assessments of leaching behavior (e.g., Petach et al. 1991, Foussereau et al. 1993, Hutson and Wagenet 1993, Wilson et al. 1993, 1996).

Inskeep et al. (1996) varied the resolution of model input parameters according to different sources of data. Model inputs were obtained primarily from detailed soil profile characterization and site-specific measurements of precipitation, irrigation, and pan evaporation for one run (Case 1). LEACHM predictions were also generated using estimated conductivity and retention functions from SSURGO textural data (Cases 2 and 3). Predictions using CMLS were generated with detailed site-specific measurements (Case 1); volumetric water contents were estimated from SSURGO textural data and daily water balance was estimated from WGEN, a weather generator(Richardson and Wright 1984) and the MAPS (Nielsen et al. 1990) climate database (Cases 2 and 3). A comparison of observed and simulated mean solute travel times showed that both LEACHM and CMLS performed adequately with high-resolution model inputs. However, model performance declined when field conditions were conducive to preferential flow and saturated hydraulic conduc- tivity values estimated from regression equations based on tex- tural data were problematic for generating adequate predictions using LEACHM. The CMLS predictions were also less sensitive to data input resolution, in part because the CMLS provides an oversimplified description of transport processes. These results demonstrate the importance of model validation and suggest why model predictions predicated on GIS-based model input data sets with low spatial resolution may not accurately reflect trans- port processes occurring in situ.

Finally, the development of new GIS tools for the process- ing and analysis of spatial data has stimulated the development of a new generation of process-based models. These models simu- late water flow as a two-dimensional function usually represented by a raster and occasionally a Triangulated Integrated Network (TIN) (e.g., CASC2d - Julien et al. 1995, r.water.fea - Vieux et al. 1996, SIMWE - Mitas and Mitasova 1998, MIT models - Garrote and Bras 1993, Willgoose and Gyasi-Agyei 1995). These models predict the water flow (water depth, discharge) at any point in the landscape and not just at the watershed outlet (as is the case with the watershed-based models). The averaged values of landscape characteristics used in the watershed models have been replaced by their distributed representation in these new models. In addition to simulating impact-specific land use prac- tices, these new models simulate the spatial pattern and locationwithin the watershed.

Spatially distributed process models can be used to provide new insights into the interactions between land use and land cover on the one hand and water flow and water quality on the other (e.g., Doe et al. 1996). However, this approach has also revealed substantial gaps in our understanding of the theory of sediment and pollutant transport processes in complex landscapes. New approaches for field experiments integrated with spatial model- ing are needed to improve our understanding of spatial interac- tions influencing water resources and, for example, to reduce the error of sediment load predictions (which are currently at about 50-150%) to acceptable and useful levels. This assessment is simi- lar to that of the National Research Council (1999: 139-163), which reviewed some of these same activities and concluded that many of our existing models are inadequate for watershed man- agement. They thought that new models directly linked to GISystems and decision support systems, incorporating all facets of watershed management and spanning a variety of scales of application, were needed. The National Research Council (1999) also envisaged a future in which these water resource models were as easy to use as a typical word processor or spreadsheet in order to serve both those who need them and the model developers.

Water Resource Decision Support Systems

Several efforts have been launched to develop and sustain water resource decision support systems. Some of these systems are aimed at research applications and others are designed to sup- port specific watershed management goals. For example, several water resource decision support systems linked with the ArcView GIS have been developed to support the assessment of the impact of urban planning on water resources (e.g., LTHIA2 - Pandey et al. 1999, HydroPEDDS - Johnston and Srivastava 1999). Two additional and, in some ways, more ambitious systems are reviewed here to illustrate the accomplishments and skills likely to be required to develop and use these systems. The examples described below are instructive on two counts: 1) they illustrate recent accomplishments and shortcomings; and 2) they indicate the types of training and skills that water resource specialists are likely to need in the 21st century.

Paniconi et al. (1999) reviewed the strengths and weaknesses of GIS and explained why distributed hydrologic models typically rely on GIS, data visualization, and other software tools for pre- and post-processing, and as complementary components of decision support systems. They developed a decision support system to estimate soil moisture from satellite measurements and validate these estimates using ground truth measurement and catchment scale hydrologic modeling. Their initial integration efforts used standard data formats, and the creation of graphic user interfaces for data and tool management and their more recent work has used computer-assisted design (CAD) frameworks. These frameworks consist of software infrastructures that were developed to integrate uncooperative, often proprietary, tools in the world of CAD. The latter approach is based on a data flow paradigm through which the modular components of an application-specific system can be connected. Such an approach may dramatically reduce the time and effort devoted to tool and data integration, although such systems may only be suited to projects involving small groups of research scientists and care must be taken to insure that these systems do not influence the direction of the research itself. Clark (1996) has observed that problem in other water resource applications, and potential problems may be compounded in situations where the science is very complicated and/or poorly understood (as illustrated in the next example).

Downs and Priestnall (1999) developed a fluvial geomorphology GIS to explore river channel adjustment processes and patterns and then tried to evaluate the advantages and disadvantages of this system. They thought that the system was useful in the sense that it had automated the estimation of several of the key parameters and that this would eventually allow them to test a series of specific hypotheses related to river channel adjustment. However, they also concluded that their system was impenetrable to non-GIS specialists (like many other highly customized applications of GIS) and that most users would be unable to extend or substantially modify the system by themselves. In its current form, this particular system can only address a subset of the processes thought to control river channel adjustment along specific reaches of a river. The complex interaction of many factors over varying spatial and temporal scales may continually preclude a deterministic understanding of river channel adjustment at the watershed scale (Howard 1996).

The above two systems are very specialized and yet remain limited in terms of both the scientific understanding incorporated in them and the numbers and types of users who can use them. Additional problems may arise if model limitations are ignored when GIS-based modeling applications are developed and unskilled users fail to recognize the impact of these short- comings on the results (Burrough 1996a). This state of affairs characterizes many of the recent attempts to implement GIS- based soil erosion models (e.g., Wilson and Lorang 1999). There is also the danger that fieldwork for model calibration, valida- tion, and scientific investigation will be neglected if model build- ing is too easy to accomplish (Burrough 1996a).

Linkages to UCGIS Research Challenges

The previous section identified some important research chal- lenges in addition to recent accomplishments. The UCGIS re- cently delineated the GIScience research agenda as a set of challenges and the discussion that follows identifies individual challenges and/or areas within these challenges that are particu- larly relevant to the water resource domain. Each of the 10 re- search challenges identified by the UCGIS intersects with specific problems encountered in water resource applications of GIScience.

Spatial Data Acquisition and Integration, Distributed Computing, Interoperability, and theFuture of Spatial Information Infrastructure

Several of the water resource applications described in the previ-ous section have benefited from the explosive growth in auto-mated data capture techniques, such as GPS, satellite imagery,and ground-based data acquisition systems. New GPS opportu-nities, satellite sensors, and short-range remote sensing instru-ments that are likely to help with the determination of subsurfacetransport parameters and non-point source pollution levels aredescribed by Corwin (1996), Wilkinson (1996), and Twigg(1998), respectively. Similarly, the recent deployment of the WSR-88D radar by the National Weather Service represents an impor-tant new data source for meteorological and hydrological projects(Crum and Alberty 1993, Vieux and Farajalla 1996). However,the use of these indirect measurements to estimate rainfall andrunoff in severe storms has its own problems. Vieux and Bedient(1998) found that WSR-88D radar reflectivity could only be usedto estimate rainfall accurately in operational flood forecasting when an appropriate reflectivity/rainfall rate relationship was usedand rain gauge accumulations were available to calibrate the radarrainfall estimates for a severe storm in south Texas. The develop-ment of these tools offers new opportunities for many more people to participate in the data collection process and requires much bet-ter tools to integrate different types of geographic data and solvespecific water resource problems. The increased interest in localenvironmental quality and the advent of "field" GIS mean thatsome of the integration will need to be performed *in situ* as well.

The reliance on multiple sources and types of data in most water resource applications indicates why the increasing avail- ability and popularity of distributed computing will promote further GIS work in this application domain. The overload at some map servers (especially those that serve maps of interest to large numbers of people, such as the EPA) demonstrates there is a strong need for high performance as well as distributed computing. High performance is required for processing data and serving the data over the Internet as well as for running complex models and certain applications (e.g., flood predictions) in near-real time.

Some progress has been made with data sharing, and metadata concepts and tools are both evolving quickly. However, the current strategies work best for information that was largely cartographic in origin, and research is still required to formalize methods for representing other types of geographic phenomena and to develop standardized languages for describing operations. These types of innovations would make it easier to integrate GIS data into dynamic models and to facilitate increased data sharing among the environmental modeling community (e.g., Paniconi et al. 1999). The launching of several new local, state, and federal data sharing programs, the increased numbers of citizens interested in local water resource issues, and the continued growth in the popularity of distributed computing will increase the need for and benefits flowing from progress in this area.

The increased interest in local communities and environmental issues at all levels of government will require technical and institutional programs to support the creation and sharing of local knowledge. New tools to capture data and advances in distributed computing provide important opportunities to identify gaps or errors in existing data and to collect new data. There is an immediate opportunity to promote the accelerated growth and utilization of geographic information resources in meeting society's water resource needs in many communities. Flood warning systems could readily be adapted to individual houses, for example. The development of spatial information infrastructure can have a dramatic impact on the role that spatial information plays in the life of every citizen in many areas, including water resources. The availability of water resources information will have an impact on planning at every level - from government, through business and farmers, to citizens purchasing new homes. Research is required to identify the best approaches for customizing the same information for different users and/or purposes.

Extensions to Geographic Representations and Cognition of Geographic Information

Many of the water resource applications described in the previous sections used traditional geographic data representations that are geared toward the representation of static situations on a planar surface at a specific scale because the data were derived from paper maps. Some of the applications have used fuzzy classification systems to represent data of varying exactness and degrees of reliability. Further work to refine these techniques, and the methods used to convey this additional information to the user, is required (e.g., De Gruijter et al. 1997). Extensions that are more effective are required to integrate GIS with dynamic modeling (e.g., Wesseling et al. 1996). These extensions will have an especially large impact in this domain because different data repre- sentations are suited to different types of applications and most solutions will require several types of information drawn from varying sources.

Most of the modeling applications summarized in this pa- per incorporate precipitation, soil, topographic, and land- cover information. Most precipitation data consist of point estimates (i.e., climate station measurements) although the WSR-88D weather radar and some of the new satellite sensors offer spatially distributed data. Topographic information may utilize the square grid, irregular point, contour, or triangulated irregular network models. Most of the soil and land-cover data sets that are cur- rently available consist of raster grids or polygons, and most river systems are presented as a series of links (stream segments) and nodes (stream junctions). There are many stratagems involved in working effectively with the different data types in an integrated environment (for examples, see Custer et al. 1996, Inskeep et al. 1996, Wilson et al. 1996, Mackay and Band 1997, Hellwegerand Maidment 1999).

Kemp (1997a, b) recently advocated the design of a level ofuser interaction that would focus on the user's concept of thefield and hide lower-level issues of field representation as far aspossible. Kemp (1997a) proposed a series of rules to guide con-versions between data models based on the number of spatialelements per unit area (i.e., the relative size or spacing of thespatial elements). Kemp (1997b) described several field variableswhose values can be used to select appropriate conversion proce-dures when working with two or more spatial data models. Theseideas need to be developed further, since the choice of field modeland conversion from one model to another are fraught with dif- ficulties (Heuvelink 1996). In a similar vein, better methods ofspatiotemporal representation for multidimensional data are alsorequired. Time is still not supported well enough, and more so-phisticated spatiotemporal analytical tools are needed (for an ex-tended discussion of current options and shortcomings, see Yuan1999 and Renolen 2000). The increasing availability of 3-D data,especially for atmospheric and groundwater modeling, is likelyto promote additional work concerned with the handling, analy-sis, and visualization of volumetric data and their change in time.The deployment of the geo-object model in ArcInfo Ver- sion 8.01 will promote further work concerned with the cogni-tion and representation of objects. Davis and Maidment (1999)are currently building customized sets of objects to describe natural systems made up of rivers and watersheds in ArcInfo. An analo-gous geo-object model has already been defined by ESRI for pipenetwork systems used to convey water and wastewater. Mackayet al. (1992) and Robinson and Mackay (1996) have shown howthe disciplinary scientist and manager might be afforded the op-portunity to work with landscape elements such as hill slopes,streams, valleys, and river reaches instead of fields, polygons, andpixels. Similarly, Burrough et al. (2000) used GIS, spatial sam-pling methods, fuzzy k-means classification, and statistical mod-eling of the derived stream topology to derive a set of meaningful,spatially coherent topo- climatic landscape classes in the Greater

Yellowstone Area. These types of extensions, which rely on logic-based systems augmented with various forms of inexact reasoning, will almost certainly be required to develop the types of easy-to-use models and decision support systems envisaged for the future by the National Research Council (1999). Sustained progress in this area is likely to improve the effectiveness of water resource decision support systems as well as GIS.

Scale Issues

Issues concerning "scale" refer to the level of detail at which information can be observed, represented, analyzed, and communicated. The development and evaluation of the "fitness for use" of topographic and hydrologic databases that extend over large areas (regions) are areas of active research as illustrated by the following account of recent work exploring the characteristics of digital elevation models and their impact on hydrologic modeling.

Many recent studies, for example, have examined the sensitivity of computed topographic attributes to the choice of data source, structure, and/or cell size. In one such study, Hammer et al. (1994) compared 30-m USGS DEMs with field data and found that they correctly predicted slope gradient at only 21% and 30% of the field sampling locations in two study sites. Srinivasan and Engel (1991), Zhang and Montgomery (1994), and Mitasova et al. (1996) found similar results, and numerous authors have argued that DEMs with spatial resolutions of 2-10 m are required to represent important hydrologic processes and patterns in many agricultural landscapes (Wilson 1999b).

Numerous studies have also shown how the choice of data source and resolution can impact model predictions. Panuska et al. (1991) and Vieux and Needham (1993) quantified the effects of data structure and cell size on Agricultural Non-Point Source pollution model input and showed how the computed flowpath lengths and upslope contributing areas varied with element size. Vieux (1993) examined the sensitivity of a surface runoff model to the effects of cell size aggregation and smoothing using different-sized windows. Moore et al. (1993) examined the sensitivity of computed slope and steady state topographic wetness index values across 22 grid spacings for three large catchments in southeastern Australia. Hodgson (1995) demonstrated that the slopes and aspects calculated from 30-m DEMs are representative of grid spacings two or three times larger than the original DEM grid spacing. Issacson and Ripple (1991) compared 1° USGS 3 arc-second and 7.5' USGS 30-m DEMs, and Lagacherie et al. (1996) examined the effect of DEM data source and sampling pattern on computed topographic attributes and the performance of a terrain-based hydrology model. Chairat and Delleur (1993) quantified the effects of DEM resolution and contour length on the distribution of the topographic wetness index as used by TOPMODEL and the model's peak flow predictions. Wolock and Price (1994) and Zhang and Montgomery (1994) also examined the effects of DEM source scale and DEM cell spacing on topographic wetness index values and TOPMODEL predic- tions. Garbrecht and Martz (1994) examined the impact of DEM resolution on extracted drainage properties for a catchment in

Oklahoma using hypothetical drainage network configurations and DEMs of increasing size. They derived various quantitative relationships and concluded that the grid spacing must be se- lected relative to the size of the smallest drainage features that are considered important for the work at hand. Bates et al. (1998) showed how high-frequency information is lost at progressivelylarger grid spacings.

More work of this type is required within and across a broad spectrum of data sources and themes. The DEM results summa- rized above give an idea of the magnitude of this task and indi- cate why only limited progress has been made despite long-standing recognition of the implications of scale for geo- graphic inference and decision-making. The gaps in our knowl- edge and lack of appropriate tools have serious consequences for most of the water resource applications described in the previous sections. Similarly, the advent of new, high-resolution data sets for large areas will allow analysis and modeling to be performed at much greater detail than is done now. The handling of large data sets in relation to scale is likely to emerge as a critical issue in the immediate future (for an example of the type of research re- quired, see Wilson et al. 1998).

Spatial Analysis and Uncertainty

Several of the innovations identified by the UCGIS would pro- duce immediate benefits in the water resource application do- main with the introduction of spatial analysis techniques that are more powerful and easy to use. Clearly, the increased availability of large, geographically referenced data sets and improved capa- bilities for visualization, rapid retrieval, and manipulation inside and outside of GIS will demand new methods of exploratory spatial data analysis that are specifically tailored to this data-rich environment (Wilkinson 1996, Gahegan 1999). Similarly, new methods that incorporate and exploit the benefits of geostatistics are required. These methods would provide descriptions of key variables that are more accurate as well as improved diagnostics for error assessments and accuracy (uncertainty) determinations. Increased knowledge of these properties can be expected to im- prove the ways in which many types of environmental data are collected, stored, analyzed, and visualized in the future (for ex- amples of soil survey applications, see Burrough et 1997, De Gruijter et al. 1997, Lark and Bolam 1997).

Other innovations are required because many of the data sets used in the water resource applications reviewed in the previ- ous section were derived inside GIS. Additional work is required to refine and/or document the consequences of using specific methods. The choice of flow routing method, for example, can have a large impact on computed terrain attributes (Wolock and McCabe 1995, Desmet and Govers 1996). The current options include the D8 (deterministic eight node (Figure 2); O'Callaghan and Mark 1984) and the Rho8 (random eight node; Fairfield and Leymarie 1991) single flow algorithms, the FD8 multiple flow algorithm (Freeman 1991, Quinn et al. 1991), and the DEMON stream tube algorithm of Costa-Cabral and Burges (1994). However, this is an active area of research and a modified form of the FD8 algorithm and new grid-vector and grid-triangular multiple flow routing algorithms were recently proposed by Quinn et al. (1995), Mitasova et al. (1996), and Tarboton (1997). Additional research is now required to determine which of these algorithms works best with different types of source data (square-grid DEMs, contours, GPS data sets, etc.) in specific environments (Wilson 1999b). The best method for a particular application will be the one that simulates or mimics the runoff processes occurring in that particular landscape. In addition, different methods may be suited to different parts of a landscape, as Mackay and Band (1998) have demonstrated for a series of lake-dominated landscapes in Ontario, Canada. The results of this type of work and the inclusion of new tools in GIS software will have important implications for the successful deployment of GIS in water resource applications.

An increased number of users with very different backgrounds will be using water resource data to make crucial decisions. The importance of finding reliable methodologies for estimating, visualizing, and using measures of uncertainty is elevated for a wide range of applications. Water data are volatile in time and space with high degrees of variation. Better use and representation of uncertainty are important for spatial data in general, but are especially significant for water resource data where a small, localized change may have a dramatic impact. Several of the research projects cited earlier have attempted to evaluate the uncertainty inherent in various data sets and/or analytical methods. It is well known that uncertainty exists in every phase of the geographic data life cycle, from data collection to data representation, data analyses, and final results. However, our knowledge of uncertainty in geographic data and its consequences for water resource decisions made using GIS is very incomplete. More work following the model of Weih and Smith (1997), who traced the influence of cell slope computation algorithms through to a common forest management decision, is urgently needed in the water resource domain.

GIS and Society

The connection between the "GIS and Society" research challenge and water resource applications is obvious because our continued prosperity and, in some cases, survival depend on effective water resource management. GIS assists in the collection, storage, analysis, and visualization of key information and thereby helps with the development of effective water resource programs and practices. Not all water resource problems require GIS and simulation models (e.g., Lovejoy 1997); however, those that do require technologically sophisticated solutions are likely to benefit from additional research and education to ensure that the GIS/modeling results can be interpreted and used appropriately.

In addition, these GIS/modeling results for water resource assessment may provide conflicting evidence or be used by groups with competing interests and power. The question of water con-trol is perhaps straightforward in a scientific sense of balancinginputs and outputs, but is far less tractable within the realm of enforcement. Classic political conflicts between urban interests and agricultural uses for electricity and recreation, navigation, flood control, and the natural environment may all find expres- sion within a GIS. Notwithstanding their precision, sophistica- tion, or persuasiveness, the outcomes will have to be settled in apolitical environment.

This political environment is changing as well, and a range of solutions will be required now and in the immediate future because of the dramatic change in watershed management that has occurred during the past 5-10 years. There has been a shift from large government-directed regulatory programs toward lo- cal initiatives, with government providing some support. The main participants are land owners, often organized into associa- tions, such as the Landcare programs in Australia and New Zealand or watershed associations in the U.S. (the EPA has al- ready more than 4000 such associations registered). This reorga- nization of participants will have a profound impact on the GIS tools required for water resources management. The target has shifted from large government organizations with professional staff. Instead, we will need tools for retrieving and analyzing wa- tershed information that can be used by people who are not spe- cialists and are located in many different places. A wider range of tools operating at the watershed and other levels of analysis, rang- ing from complex and sophisticated to the very simple, will be needed. The National Research Council (1999), for example, recently argued that watersheds as geographic areas are the natu- ral organizing units for dealing with the management of water and numerous other closely related problems.

Linkages to UCGIS Education Challenges

The research applications and challenges give some indication as to the types of skills and backgrounds that will be required by the next generation of water resource specialists. The UCGIS recently described the GIScience education agenda as a series of funda- mental topics and the following discussion identifies individual topics and/or areas within these topics that are particularly rel- evant to the water resource domain. Many of our educational establishments will need to improve their supporting infrastruc- ture and modify their curricula to provide the two required sets of improvements.

The first set of educational improvements addresses the strengthening of the GIScience curriculum. The UCGIS model curriculum project that is now underway is an important inno- vation in this regard, although its final impact will depend on the redeployment of resources and rates of adoption. The current draft specifies education and training goals and content for four levels of users: 1) informed users among the general population,
2) disciplinary analysts, 3) GIScience analysts, and 4) GIScience developers. Most of the existing academic programs are aimed at level 1 users and many of these programs will need to be reorga- nized and expanded to serve the users in the three other levels. These changes can be articulated as part of a second and much broader set of educational goals as noted below.

The second set of improvements is tied to multidisciplinary education and the need to build stronger and more substantial links between the science, engineering, and policy programs that intersect with the water resource application domain. Deliberate planning and skillful identification and negotiation of tradeoffs will be required to foster these types of linkages inside universities. The rewards of such an approach will be substantial, although their exact character can be expected to vary by discipline. Bouma (1997), for example, advocated a future in which soil scientists operate as "knowledge brokers" with skills that can support both general assessments (synthesis) and detailed investigations (new research). Wilson and Burrough (1999) advocated adding fuzzy classification, geostatistics, and dynamic modeling to physical geography curricula. Geographers, in general, will need to strengthen their computer and quantitative methods skills if they are to retain their key role in GIScience education, research, and outreach. Similarly, computer science and engineering participants would benefit from formal geographical training. These examples indicate that we should equip the next generation of scientists with broad as well as deep knowledge and skills and the ability to communicate the goals, methods, results, and utility of their research at varying levels of certainty to a variety of stakeholders. The growth in professional education programs and their use of emerging technologies to deliver GIScience education (e.g., GIScience Graduate Certificate Programs at Pennsylvania State University and the University of Southern California, and the ESRI Virtual Campus) may improve access, help to facilitate these types of changes, and divert some of the focus from research-driven graduate GIS education. The multidisciplinary character of the water resource application domain adds another level of complexity to the task of integrating curricula serving the GIScience and water resource application domain. The inclusion of formal geographical training in science and engineering curricula and the development of GIScience courses aimed specifically at these audiences offer the best chance to accomplish the types of outcomes advocated here.

Priority Areas for Research and Education

The National Research Council (1999) recently advocated a watershed management future that aims to develop careful, long-term solutions to problems and provides sustainable access to resources. Four sets of innovations were identified as necessary to achieve these goals:

- The development of simulation models that work. Models that describe the physical system, including the linkages and feedbacks between different components, and how management actions might affect the system are needed.
- The development of GIS, simulation models, and spatial decision support systems that are easy to use. These tools should be as easy to use as today's word processors and spreadsheets to accommodate the large numbers and types of users, stakeholders, etc.
- The identification and adoption of inexpensive, useful water resource indicators. These indicators will increase and/or

improve data collection and will help in monitoring progress,compliance, etc.

- The development of improved methods to quantify the risk and uncertainty incorporated in the decision-making process.

The assessment of the current status of water resource appli- cations of GIS offered in the section on major GIScience contri- butions and their significance suggests that most, if not all, of these innovations can only be implemented with the assistance of GIS. The discussion of the linkages to the UCGIS research challenges indicates that additional research will be required for this to happen. Some of the research challenges identified by the UCGIS two years ago are driven as much by changes outside GIS and their significance to water resource applications of GIS is modest at best. The topics concerned with spatial data acquisi- tion and integration, distributed computing, interoperability, the future of the spatial information infrastructure, and the connec- tions between GIS and society might be classified this way. Progress on the remainder of the research challenges outlined by the UCGIS will require substantial contributions from GIScientists and/or special attention to the water resource do- main. Advances in three broad areas are required:

- The development of new models and research to demon- strate how well and when they mimic the real world. These models will almost certainly be dynamic and incorporate geographically distributed inputs that are derived from mea- surement and interpolation. The interpolation will utilize geostatistics, fuzzy logic, and other forms of inexact reason- ing. Some of the models will be implemented inside GIS (e.g., MIKE BASIN model developed by the Danish Hy- draulic Institute) and others will include GIS functions (e.g., MIKE SHE model developed by the Danish Hydraulic In- stitute). Both types of models may be embedded in spatial decision support systems.
- Continued work on representation issues. The advent of field computing and several new remote sensing data collection tools coupled with the storage and distribution capabilities of the Web will greatly increase the volume and quality of information that is potentially available. These tools will generate many more representation (e.g., Kemp 1997a, b, Robinson and Mackay 1996, Davis and Maidment 1999) and classification options (e.g., Corbett and Carter 1996). These innovations, in turn, will promote the continued de- velopment of new geographically distributed models such as those of Julien et al. (1995), Mitasova et al. (1996), and Vieux et al. (1996).
- The development and inclusion of new spatial analysis func- tions inside GIS and/or spatially distributed water resource simulation models and decision support systems. For ex- ample, the latest terrain analysis, fuzzy logic, geostatistics (i.e., interpolation), and visualization (i.e., 3-D animations to show spatially varying patterns through time) tools might be extended (e.g., Mitas et al. 1997, Mitas and Mitasova

1998, Wilson and Burrough 1999). Additional research is also required to specify rules and guidelines for when these tools should be used since the applicability of specific functions and tools is likely to vary with the choice of data theme and/or landscape (e.g., Mackay and Band 1998).

Sustained progress on these GIScience research challenges and the delivery of the types of simulation models and spatial decision support systems envisaged by the National Research Council (1999) has tremendous implications for education as well. Of the two sets of necessary improvements mentioned in the previous section, the need to build stronger and more substantial multidisciplinary links is not receiving as much attention as the specification of the GIScience model curriculum. A Model Curriculum Task Force funded by ESRI is currently working on the GIScience model curriculum. In considering multidisciplinary education for the water resource application domain, three categories of students are to be considered: 1) those familiar with water resources but not with GIS, 2) those familiar with GIS, but not with water resources, and (3) those familiar with neither. One of the most pressing problems in reaching all three categories of students is how best to insert GIS-related education and training into curricula that are already quite full, particularly in engineering and agricultural programs. To this end, the "Learning with GIS" education challenge of the UCGIS is especially pertinent. GIS is an excellent teaching tool for introducing and exploring many aspects of water resources, including resource monitoring, water storage and flow in rural and urban communities, stream flow monitoring, surface and groundwater hydrology, irrigation engineering, farming practices, wetlands ecology, water pollution, and many others. Three high-priority recommendations in the context of "Learning with GIS" include:

- Teaching modules and laboratory exercises. A broad range of water resources education modules should be developed and utilized in existing undergraduate/graduate lectures and/or labs, thus alleviating the problem of adding whole courses to curricula that are already full. A unifying concept on which to base the modules, regardless of what course they should be used in, is the hydrologic cycle. Once developed, these modules should be distributed free of charge on the Web. As a start, the new National Center for Geographic Information and Analysis core curriculum in geographic information science will include a water resource application unit. Outstanding issues still to be considered include: 1) At what level should most of the modules be developed (lower division undergraduate or upper division)? 2) If a module includes the linkage of hydrological modeling techniques with GIS software, will the models need to be simplified for the purposes of teaching? 3) How best to include the international context of water resources education? What overseas educational resources can be used in the development of modules (e.g., instructors in the Middle East who teach water policy issues)?

- With respect to professional education, a set of modules should be developed that treats water resources from the point of view of a manager (working for a water management board, water district, extension office, county, state, federal government, etc.) or a farmer. Rather than a “plug in,” these modules should form the basis of a one- or two-day short course that might be offered over the Web, as a video con- ference, or in conjunction with a professional association’s meeting or a water resources conference.
- Data sets for teaching. Water resource GIS data sets specifi- cally for teaching are often difficult to locate. For example, the EPA “Surf Your Watershed” Web site, while an extraor- dinary source of maps and numbers, does not include data in GIS-ready format for university- or secondary-level in- structors. This was not its purpose. The availability of teach- ing data sets for a broad range of water resource applications is sorely needed, along with additional guidelines to aid in- structors in adding data sets localized to their own geographic area so that concepts are even easier for students to absorb. Good examples of GIS-ready data sets for instruction in water resources can be found at the University of Texas and San Diego State University. Synthetic data sets that could be used to test GIS methods would also be invaluable. Finally, a Web- based bibliography of data sources and metadata describing the quality, accuracy, and appropriate use of these data sets would promote the continued growth in the number and variety of high-quality water resource applications of GIS.

Conclusions

Water resource assessment and management are inherently geo- graphical 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 wa- ter resource problems during the past decade. GISs have ex- panded the number of ways information can be presented and thereby extended their accessibility, and many of the most popu- lar spatially distributed data sets can now be accessed via the Internet. Similarly, there has been a steady increase in the num- ber and variety of functions incorporated in GISs that are suited to water resource applications. GIScience has also influenced the development and implementation of hydrologic models at several different levels. For example, GISs have provided tools to compute averaged values more efficiently and to include at least some level of spatial effects by partitioning entire water- sheds into sub-watersheds in both site-specific and lumped pa- rameter models. Similarly, geographic information technologies have played a major role in the development of distributed hy- drologic models. These models offer the best chance for im- proving our understanding of spatial processes and patterns affecting the distribution and movement of water in landscapes as well as the impact of land use on water resources over the long term. In addition, the gradual demise of stand-alone GISs and the inclusion of GIScience tools and data in the general computing infrastructure suggests that GIScience is likely to become an integral part of these types of water resource modeling and decision support systems in the future.

This particular vision of the future is shared by the National Research Council (1999) in their report identifying strategies for providing careful, long-term solutions to water resource problems and sustainable access to water resources in the U.S. Their final report identifies numerous gaps and shortcomings in our existing water resource applications of GIS, simulation models, and decision support systems. The National Research Council (1999) concluded that the four sets of innovations sumarized n the previous section are necessary to achieve this future. Theseinnovations would utilize and, in turn, have significant implica- tions for GIScience research and education. In particular, theirreport indicates that there is a continued need for research on thedevelopment and evaluation of new models, representation is- sues, and the development and inclusion of new spatial analysis functions in GISs and water resource decision support systems. Similarly, our education institutions can look forward to a seriesof difficult choices as they search for creative solutions that bal-ance the need for GIScience training across a number of scienceand engineering curricula with the need for multiple levels ofinstruction within the GIScience community. Sustained progress in each of these areas will be required if we are to construct easy-to-use simulation models and decision support systems that helpto identify and solve real-world water resource problems.

References

Arnold, J.G., P.M. Allen, and G. Bernhardt, 1993, A Compre- hensive Surface-groundwater Flow Model. *Journal of Hydrol-ogy*, 142, 47-69.

Band, L.E., 1986, Topographic Partition of Watersheds with Digi- tal Elevation Models. *Water Resources Research*, 22, 15-24.

Bardossy, A. and M. Disse, 1993, Fuzzy, Rule-based Models forInfiltration. *Water Resources Research*, 29, 373-382.

Bardossy, A. and L. Duckstein, 1995, *Fuzzy Rule-Based Modeling with Applications to Geophysical, Biological, and EngineeringSystems* (New York: CRC Press).

Bates, P.D., M.G. Anderson, and M. Horrit, 1998, Terrain In- formation in Geomorphological Models: Stability, Resolu- tion, and Sensitivity. In Lane, S.N., K.S. Richards, and J.H. Chandler (Eds.), *Landform Monitoring, Modeling, and Analy- sis* (New York: John Wiley and Sons), 279-310.

Bliss, N.B. and W.U. Reybold, 1989, Small-scale Digital Soil Maps for Interpreting Natural Resources. *Journal of Soil andWater Conservation*, 44, 30-34.

Bolstad, P.V. and T. Stowe, 1994, An Evaluation of DEM Accuracy: Elevation, Slope, and Aspect. *Photogrammetric Engineering and Remote Sensing*, 60, 1327-1332.

Bouma, J., 1997, The Role of Quantitative Approaches in Soil Science when Interacting with Stakeholders. *Geoderma*, 78, 1-
.

Davis, T.J. and C.P. Keller, 1997, Modeling Uncertainty in Natural Resource Analysis using Fuzzy Sets and Monte Carlo Simulation: Slope Stability Analysis. *International Journal of Geographical Information Science*, 11, 409-434.

De Gruijter, J.J., D.J.J. Walvoort, and P.F.M. van Gaans, 1997, Continuous Soil Maps: A Fuzzy Set Approach to Bridge the Gap between Aggregation Levels of Process and Distribution Models. *Geoderma*, 77, 169-195.

Deichmann, U., 1994, *A Medium Resolution Population Database for Africa* (Santa Barbara, CA: National Center for Geographic Information and Analysis, University of California).

Desmet, P.J.J. and G. Govers, 1996, Comparison of Routing Algorithms for Digital Elevation Models and Their Implications for Predicting Ephemeral Gullies. *International Journal of Geographical Information Systems*, 10, 311-331.

Djokic, D. and D.R. Maidment, 1991, Terrain Analysis for Urban Storm Water Modeling. *Hydrological Processes*, 5, 115-124.

Doe, W.W., B. Saghafian, and P.Y. Julien, 1996, Land Use Impact on Watershed Response: The Integration of Two-dimensional Hydrological Modeling and Geographical Information Systems. *Hydrological Processes*, 10, 1503-1511.

Downs, P.W. and G. Priestnall, 1999, System Design for Catchment-scale Approaches to Studying River Channel Adjustments using a GIS. *International Journal of Geographical Information Science*, 13, 247-266.

Fairfield, J. and P. Leymarie, 1991, Drainage Networks from Grid Digital Elevation Models. *Water Resources Research*, 27, 709-717, 2809.

Federal Geographic Data Committee, 1995, *Content Standards for Digital Geographic Metadata* (Washington, DC: Federal Geographic Data Committee).

Fisher, P., J. Dykes, and J. Wood, 1993, Map Design and Visualization. *Cartographic Journal*, 30, 136-142.

Foussereau, X., A.G. Hornsby, and R.B. Brown, 1993, Accounting for the Variability Within Map Units When Linking a Pesticide Fate Model to Soil Survey. *Geoderma*, 60, 257-276.

Freeman, G.T., 1991, Calculating Catchment Area with Divergent Flow Based on a Regular Grid. *Computers and Geosciences*, 17, 413-422.

Gao, J., 1997, Resolution and Accuracy of Terrain Representation by Grid DEMs at a Micro-scale. *International Journal of Geographical Information Science*, 11, 199-212.

Gahegan, M., 1999, What is Geocomputation? *Transactions in GIS*, 3, 203-206.

Gahegan, M. and J. Flack, 1999, The Integration of Scene Understanding within a Geographic Information System: A Pro- totype Approach for Agricultural Applications. *Transactionsin GIS*, 3, 31-50.

Garbrecht, J. and L.W. Martz, 1994, Grid Size Dependency of Parameters Extracted from Digital Elevation Models. *Computers and Geosciences*, 20, 85-87.

Garrote, L. and R.L. Bras, 1993, *Real-time Modeling of River Basin Response using Radar-generated Rainfall Maps and a Distributed Hydrologic Database* (Cambridge, MA: MIT), 15-180.