Application of Remote Sensing and Geographic Information Systems on Water Resources Management

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Abstract: Water is a primary source of life and is required in sufficient quantity and acceptable quality to sustain all human activities such as domestic, agricultural and industrial needs. This requirement however, is hardly fulfilled due to various natural and anthropogenic activities. Remote sensing and Geographic Information System (GIS) techniques are useful in hydrological research and applications. Remote sensing observations enable improved characterization of the land surface which are relevant in hydrological studies. Remote sensing with its merits of providing spatially extensive, multi-temporal and cost effective data, has become a very handy tool in identifying hydrogeological processes. These studies have revealed the application of integrated remote sensing and GIS technologies in groundwater exploration and exploitation. Integrated remote sensing and GIS are widely used in groundwater mapping. Locating potential groundwater targets is becoming more convenient, cost effective than invasive methods and efficient with the advent of a number of satellite imagery. The nature of remote sensing-based groundwater exploration is to delineate all possible features connected with localization of groundwater. Data, driven out of remote sensing, support decisions related to sustainable development and groundwater management. Integration of remotely sensed data, GPS, and GIS technologies provides a valuable tool for monitoring and assessing water pollution. Remotely sensed data can be used to create a permanent geographically located database to provide a baseline for future comparisons hydrological studies. The integrated use of remotely sensed data, GPS, and GIS will enable consultants and natural resource managers to develop management plans for a variety of natural resource management applications.

Keywords: Remote sensing, water resources management, geographic information system, hydrology, GIS applications, natural resource applications.

1. INTRODUCTION

Water resource applications of GIS are concerned with the hydrologic cycle and related processes. They are multi-faceted because: (1) many of the problems involve interactions between the hydrosphere, atmosphere, lithosphere, and biosphere; (2) solutions must serve competing groups of users; and (3) many of the important hydrologic processes have local, regional, national, and global dimensions. With the advance in space technology, it is now possible to employ remote sensing techniques for estimating surface and subsurface water over large areas. These methods are very useful for rapid groundwater mapping of large and inaccessible areas. The necessity of remote sensing based groundwater exploration is to demarcate and delineate all possible features connected with localization of groundwater. These features are extracted from the appropriate satellite data products and integrated with the thematic details obtained from topographic sheets of the desired scale.

Modern life as we know it depends on our ability to match the supply and demand of water of appropriate quality to specific communities and users at specific times or rates. Our cities, farms, parks, and recreation areas all require water and their success (i.e. sustainability) relies on natural and human water delivery systems. Large amounts of time and effort are invested in learning more about the spatial and temporal patterns and characteristics of individual hydrologic processes so we can anticipate, manage, and modify system behavior to sustain modern lifestyles and prevent shortages (droughts), surpluses (floods), and resource impairment (pollution). Concerns about numerous issues, such as population growth, point source pollution, soil degradation, food supply, and energy have eased somewhat over the past years with many positive trends. Several other water-related issues, notably those concerned with water supply, non-point source pollution, and surface and groundwater quality impairment are still issues of great concern globally.

Solving this second set of water resource problems will require an improved understanding of the fundamental physical, biological, economic and social processes, and a better knowledge of how all these components operate together within watersheds. For example, the National Research Council (1999, 2-8) [1] recently identified five sets of improvements that will be required to improve our management of water resources:

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- Increased knowledge of the linkages among watershed components (rivers, wetlands, groundwater, uplands, etc.).
- Increased understanding of the feedbacks among processes operating at different spatial and temporal scales.
- Increased availability of inexpensive, useful indicators of watershed conditions and quantitative methods to evaluate land use and watershed management practices.
- Increased availability of advanced watershed simulation models that are useful to and can be operated by managers who are not scientific experts.
- Increased understanding of the roles of risk and uncertainty in the decision-making process.

Viewed this way, water resource assessment and management are inherently geographical activities. Some combination of GIS and simulation models will be required to improve our knowledge in these areas. GIS offers powerful new tools for the collection, storage, management, and display of map-related information, whereas simulation models can provide decision-makers with interactive tools for understanding the physical system and judging how management actions might affect that system [1]. The five subsections that follow illustrate some of the ways in which GIS has already been used to advance water resource management.

1.1. GIS and Hydrologic Modeling

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

First and foremost, GIS have provided new opportunities to develop and run fully distributed models efficiently. These models take into account and predict the values of studied phenomena at any point within the watershed (e.g. [2-6]. This is very important from the point of view of management, as it allows users, for example, to identify the location of possible sources of pollution.

Second, GIS has also allowed users to run more traditional lumped models more efficiently and to include at least some level of spatial effects by partitioning entire watersheds into smaller sub-watersheds. Hence, Shamsi (1996) [7] combined a planning level GIS with the Penn State lumped parameter Runoff Model (PSRM) and used them to implement a watershed-wide storm-water management plan in one such application. Storm-water management aims to prevent or mitigate the adverse impacts related to conveyance of excessive rates and volumes of storm-water runoff. Watershed-wide approaches are required to avoid shifting the location and/or increasing the magnitude of the problem downstream. The GIS was used to estimate the physical site parameters required by the model. Both vector and raster systems were used depending on the size of the study area (watershed) and several of the inputs were derived from simple GIS overlays and lookup tables. PSRM is a single event simulation model that incorporates Soil Conservation Service (SCS) techniques for infiltration, the kinematic wave method for overland flow, and non-linear routing for storage. The model was calibrated with observed hydrograph data, and used to simulate runoff hydrographs for various durations and frequencies and to create peak flow presentation and release rate tables from the simulated hydrographs. The information summarized in these tables was then 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 storm-water management plans. The adoption of this approach in six of Pennsylvania’s 356 designated watersheds indicates that the PSRM and GIS integration offers cost-effective and technically sound solutions to Pennsylvania’s watershed-wide storm-water management problems. Djokic and Maidment (1991) [8] used ARC/INFO to simulate the drainage system and assess whether or not 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 the contributions from surface terrain (i.e. overland flow), man-made structures (i.e. pipes and channels), and storm water intakes.

This type of application is now very common and numerous lumped parameter models (HEC-1, HEC2, MODFLOW, SHE, SWAT, etc.) have been linked to GIS in these ways to predict surface and ground water flows. Orzol and McGrath (1992) [9], for example, described how the structure of MODFLOW was altered to facilitate its integration with ARC/INFO and they demonstrated that the results were the same as if the model was run as a standalone product. Similarly, Hellweger and Maidment (1999) [10] automated a procedure to define and connect hydrologic elements in ARC/INFO and ArcView and write the results to an ASCII file that is readable by the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). The modular structure and availability of source code have favored the use of the GRASS GIS in many of these environmental modeling applications (see [4, 11, 12, 6]; for additional examples). Watkins *et al.* (1996) [13] compared the advantages and disadvantages of different 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) [14] reviewed many of the recent attempts to develop models inside GIS and geographic modeling systems. The latter aim to provide libraries of landscape simulation components from which watershed simulation models can be assembled to represent user-specified processes and problems in watersheds of interest (e.g. [15-17]). The accomplishments of the Danish Hydraulic Institute are particularly noteworthy in this regard. They have implemented numerous modeling systems for river basins, urban drainage, sewer systems, rivers and channels, estuaries, and coastal waters during the past decade and since 1998 have embarked on an ambitious program to link their models with the ESRI family of GIS products. Many of their modeling systems now support GIS data transfer and one, MIKE BASIN which provides a versatile decision support system for integrated water resources planning and management, runs inside the ArcView GIS.

Third, GIS has been used to transform what were originally site-specific models into spatially distributed models. Carbone *et al.* (1996) [18], for example, combined GIS and remote sensing technologies with the SOYGRO [19] 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 (photosynthesis, respiration, tissue synthesis, translocation of protein, senescence, etc.) to environmental conditions. SOYGRO has been tested in a variety of environments and has proven reliable in estimating yield in well-managed conditions [20]. The ARC/INFO 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 six-year period (1986-91) in this instance. The results showed that the spatial variability in simulated county yield was large and linked to soil moisture availability. This soil property is a function of available water holding capacity and the timing and amount of precipitation, both of which varied greatly across space. Carbone *et al.* (1996) [18] concluded that the examination of spatial patterns of simulated yield improved county production estimates and identified vulnerable areas during droughts.

These types of assessments take many different forms and have been conducted for larger areas as well [21]. Corbett and Carter (1996) [22], for example, showed how GIS can be used to: (1) synthesize and integrate many more data than in the pre-computer (pre-GIS?) era; and (2) shift the design of agro-ecological and agroclimatological studies towards user-specified classifications. Their analysis focused on Zimbabwe, a semi-arid country where a national agroecological classification and map, the Natural Regions scheme [23], has been widely used in agricultural research and policy-making. This map used rainfall and temperature data to calculate effective rainfall and vegetation to interpolate this variable between stations. Corbett and Carter (1996) [22] constructed seasonal rainfall surfaces for Zimbabwe using decadal (i.e. ten day) rainfall data (82-99 stations; 31 years of data), the African DEM (13,400 grid points) produced by Hutchinson *et al.* (1996) [24], and the ANUSPLIN climate interpolation procedures described by Hutchinson (1995a, b) [25, 26]. They generated surfaces showing mean rainfall and annual rainfall anomalies to describe the main rainfall period (March-October) for Zimbabwe in terms of rainfall variability. They demonstrated that the natural regions experienced considerable spatial variability in terms of mean and inter-seasonal variability of rainfall. Corbett and Carter (1996) [22] then combined these surfaces with those of Deichmann (1994) [27] to show that only 19% of Zimbabwe’s population lives in areas that can expect to receive more than 600mm of rainfall (which serves as an approximate threshold for maize cultivation in southern Africa) with 75% probability.

Fourth, GIS is sometimes used to vary model inputs and compare model outputs with field data in hopes of improving the scientific basis of key water quality policies and management plans. Inskeep *et al.* (1996) [28], for example, compared several modeling approaches that might be applicable for classifying the USDA-NRCS County Soil Survey Geographic database (SSURGO; Bliss and Reybold 1989 [29], Reybold and TeSelle 1989) [30] 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 two-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 1-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 [31]. LEACHM is a 1-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 [32]. Several attempts have been made to combine both of these models with GIS databases for regional scale assessments of leaching behavior (e.g. [33-37].

Inskeep *et al.* (1996) [28] 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). CMLS predictions were generated using detailed site-specific measurements (Case 1), and volumetric water contents estimated from SSURGO textural data and daily water balance estimated from WGEN (Richardson and Wright 1984) [38] and the MAPS (Nielsen *et al.* 1990) [39] climate database (Cases 2 and 3). Comparison of observed and simulated mean solute travel times produced the following results. First, both the LEACHM and CMLS performed adequately with high-resolution model inputs. Second, model performance declined when field conditions were conducive to preferential flow. Third, saturated hydraulic conductivity values estimated from regression equations based on textural data were problematic for generating adequate predictions using LEACHM. Fourth, the CMLS predictions were 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 based on GIS-based model input data sets with low spatial resolution may not accurately reflect transport processes occurring *in situ*.

The future is some way off, in part, because geographic information technologies are relatively new and still near the lower end of the growth curve in terms of: (1) applications and (2) their influence as tools on the ways in which scientific inquiries and assessments are conducted (Goodchild 1996) [40]. Several additional challenges related to our knowledge of specific processes and scale effects that must be overcome to achieve this future are noted below as well. The National Research Council (1999, 139-63) [1], for example, reviewed some of these same activities and concluded that many of our existing models are inadequate for watershed management. New models are required that are directly linked to geographic information and decision support systems, incorporate all facets of watershed management, and span a variety of scales for application. The National Research Council (1999) [1] envisaged a future in which models were as easy to use as a typical word processor or spreadsheet in order to serve both those that need them and those that created them.

1.2. New GIS Data and Tools

The steady increase in the number and variety of functions incorporated in GIS that are suited to water resource applications during the past 5-10 years shows that some progress has been made. This trend is best exemplified by the GRASS GIS environment whose open architecture is particularly suited to the rapid prototyping of new functions in support of environmental modeling applications. The incorporation of several new terrain analysis tools, thin-plate splines, kriging, and related geostatistical techniques represent very important innovations in this respect (e.g. the inclusion of ANUDEM [40] elevation gridding procedure in ARC/INFO (Versions 7.0 and higher). ANUDEM and TOPOGRID (as it is called in ARC/INFO) take irregular point or contour data and create square-grid DEMs. The procedure automatically removes spurious pits within user-defined tolerances, calculates stream and ridge lines 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 [41]. The increased availability of GPS-derived elevation data [42] and difficulty of using published USGS DEMs for hydrologic studies documented by Hammer *et al.* (1994) [43], Zhang and Montgomery (1994) [44], Hodgson (1995) [45] and Mitasova *et al.* (1996) [46] suggest an important role for these types of tools in the future.

Several recent projects have also compared tools and/or input data. In one such study, Bolstad and Stowe (1994) [47] evaluated the accuracy of elevations, slopes, and aspects computed from USGS 30m and SPOT-STX DEMs. Their results showed that the Gesalt Photomapper-derived USGS DEM provided a better representation of microtopography. Gao (1996) [48] examined the impact of DEM resolution on the accuracy of terrain representation and slope gradients in three distinctive study areas. The results showed that representation accuracy decreased moderately at intermediate resolutions and sharply at coarse resolutions in all three types of terrain. Resolution changes also had a large impact on computed slope gradients. One would expect even larger impacts for topographic attributes that are calculated as second derivatives, such as plan and profile curvature [49, 50] defined a series of objective criteria for evaluation of the quality of digital terrain models derived from contour lines. These criteria were used to evaluate four different interpolation procedures: The r. surf. contour procedure in GRASS (Version 4.1), the MDIP procedure developed by Carla' and Carrara [51, 52], the ArcTin procedure in ARC/INFO (Version 7.0), and the Terrain Modeler procedure in Intergraph's MGE GIS (Version 5.0). The first two procedures generated square-grid DEMs and the last two procedures generated TINs. These methods were applied to three sample areas and the results showed that the MDIP and Terrain Modeler techniques performed best in that they produced terrain models that reflected the ground surface as expressed by the input contour lines.

There has also been a gradual but steady increase in the spatial content of hydrologic data sets. Hutchinson *et al.* (1996) [24], for example, describe 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^{o}C and monthly mean precipitation to within errors of about 10-30% [24]. Similarly, Graham *et al.* (1999) [53] describe 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', $1/2^{o}$, and 1^{o} resolutions globally. Both of these data sets will be useful in fully coupled land-ocean-atmosphere models, terrestrial ecosystem models, and macroscale hydrologic modeling studies.

The shift in conceptual paradigms of soil survey and mapping that has occurred during the past 30 years represents another important innovation [54]. The early models, exemplified by the STATSGO and SSURGO databases, used crisp classes in attribute space linked to crisply delineated 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 (see McBratney and Odeh 1997 [55] for a description of the basic strategy). 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 [56, 57]. These concepts and the accompanying tools have been applied most often to soil attributes but they are equally adept at describing other types of environmental variation [58]. The recent work of Bardossy and Disse [113], Bardossy and Duckstein [59], Mitasova *et al.* [46], Mitas *et al.* [4], and Mitas and Mitasova [6] illustrate the potential benefits of using these types of innovations to develop spatially distributed hydrologic models.

1.3. 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 support specific watershed management goals. 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. Two recent systems are reviewed here to illustrate the accomplishments and skills that are likely to be required to develop and use these systems.

Paniconi *et al.* (1999) [60] reviewed of 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 CAD frameworks. These frameworks consist of software infrastructures that were developed to integrate uncooperative, often proprietary tools, in the world of computer aided design. 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) [61] has observed the last problem in other water resource applications, and the 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) [62] 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 addition, this particular system (in its current form) can only address some of the processes thought to control river channel adjustment along specific reaches of a river. This is a problem in this instance because the complex interaction of many factors over varying spatial and temporal scales may always preclude a deterministic understanding of river channel adjustment at the watershed scale [63].

The above two systems are very specialized and yet 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 glossed over when GIS-based modeling applications are developed and unskilled users fail to recognize the impact of these shortcomings on the results [64]. This state of affairs characterizes many of the recent attempts to implement GIS-based soil erosion models for example [65]. There is also the danger that fieldwork for model calibration, validation, and scientific investigation will be neglected if model building is too easy [64].

1.4. Improved Visualization

Advances in computer hardware and software have greatly improved visualization during the past 5-10 years. Mitas *et al.* (1997) [66] used several case studies to illustrate the role of exploratory cartographic visualization in the development and presentation of models of landscape processes and patterns. Their approach integrates knowledge from GIS, computer cartography and scientific visualization, and supports advanced visual analysis of multivariate geo-referenced data by displaying multiple surfaces and volumes in an appropriate projection of 3-D space together with point and vector data. These visualizations can be implemented on the WWW and animated to show change through time. Dynamic cartographic models are now used as either a process of research and discovery with visualizations feeding refinements of models, or as a method of communicating complex measured or modeled geographic phenomena, which is frequently encountered in water resource applications. Other examples of work of this type include Hibbard and Santek, Fisher *et al.* Rhyne *et al.* Hibbard *et al.* and Brown *et al.* [67-71]. Another important development has involved the extension of interactive visualization capabilities to cartographic models accessible through the Internet using VRML. 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 directly interact with the landscape and models (in real time) (e.g. Johnston and Reez) [72].

2. LINKAGES TO UCGIS RESEARCH CHALLENGES

The application examples highlighted in the previous section identified some important research challenges in addition to recent accomplishments. The UCGIS recently described the GIScience research agenda as a series of fundamental topics and the discussion that follows identifies individual topics and/or areas within these topics that are particularly relevant to the water resource domain. Each of the ten research topics identified by the UCGIS intersects with the challenges and problems encountered in water resource applications of GIS.

2.1. Spatial Data Acquisition and Integration

Several of the water resource applications described in the previous section have benefited from the explosive growth in automated data capture techniques, such as GPS, satellite imagery, and ground-based data acquisition systems. The new GPS opportunities, satellite sensors, and short-range remote sensing instruments that are likely to help with the determination of subsurface transport parameters and non-point source pollution levels are described by Twigg [42], Wilkinson [73] and Corwin [74], respectively. Similarly, the recent deployment of the WSR-88D radar by the National Weather Service represents an important new data source for meteorological and hydrological projects [75, 5]. However, the use of these indirect measurements to estimate rainfall and runoff in severe storms has its own problems. Vieux and Bedient (1998) [76] found that WSR-88D radar reflectivity could only be used to accurately estimate rainfall in operational flood forecasting when an appropriate reflectivity/rainfall rate relationship was used and rain gauge accumulations were available to calibrate the radar rainfall estimates for a severe storm in south Texas. The development of these tools offers new opportunities for many more people to participate in the data collection process and requires much better tools to integrate different types of geographic data and solve specific water resource problems. The increased interest in local environmental quality and advent of "field" GIS means that some of the integration will need to be performed in the field as well.

2.2. Distributed Computing

The reliance on several different sources and types of data in most of the water resource applications described in the previous section indicates why the increasing availability and popularity of distributed computing will promote further GIS work in this application domain. The continued development of metadata concepts and tools will be required as well, and the overload at some map servers (especially those which 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 the data and serving them over the Internet, and for running complex models and certain applications (e.g. flood prediction) in near-real time.

2.3. Extensions to Geographic Representations

Many of the water resource applications described in the previous section used traditional geographic data representations that are geared towards 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.*) [77]. There is also a need for more effective extensions to integrate GIS with dynamic modeling (e.g. Wesseling *et al.*) [78]. These extensions will have an especially large impact in this domain because different data representations 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 paper incorporated 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 currently 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 tricks involved in working effectively with these different data types (see Custer *et al.* [79]; Inskeep *et al.* [28]; Wilson *et al.* [37]; Mackay and Band [80]; and Hellweger and Maidment [10] for examples).

Kemp (1997a, b) [81, 82] recently advocated the design of a level of user interaction that would focus on the user’s concept of the field and hide lower level issues of field representation as far as possible. Kemp (1997a) [81] proposed a series of rules to guide conversions between data models based on the number of spatial elements per unit area (i.e. the relative size or spacing of the spatial elements). Kemp (1997b) [82] described several field variables whose values can be used to select appropriate conversion procedures when working with two or more spatial data models.

These ideas need to be developed further, since the choice of and conversion from one field model to another is fraught with difficulties [83]. In a similar vein, better methods of spatio-temporal representation for multidimensional data are also required. Time is still not supported well enough and more sophisticated spatio-temporal analytical tools are needed (see Yuan [84] and Renolen [85] for extended discussion of current options and shortcomings). The increasing availability of 3-D data, especially for atmospheric and groundwater modeling, are likely to promote additional work concerned with the handling, analysis, and visualization of volumetric data and their change in time.

2.4. Cognition of Geographic Information

Some of the innovations noted towards the end of the previous section point to steady but sustained progress in terms of our cognition and presentation of objects. In addition, Mackay *et al.* [86] and Robinson and Mackay [87] recently indicated how the disciplinary scientist and manager may be afforded the opportunity to work with landscape elements such as hillslopes, streams and valleys, and river reaches instead of fields, polygons, and pixels. These types of extensions, which rely on logic-based systems augmented with various forms of inexact reasoning, may be required to develop the types of easy to use models and decision support systems described earlier. Sustained progress in this area is likely to improve the effectiveness of digital libraries and water resource decision support systems as well as GIS.

2.5. Interoperability of GIS

Many water resource applications require multiple systems, data sources, and enormous quantities of time and effort are expended to integrate these components (e.g. Carbone *et al.* [18]; Shamsi) [7]. Some progress has been made with data sharing and both metadata concepts and tools are 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 facilitate increased data sharing among the environmental modeling community (e.g. Paniconi *et al.* [60]. The launch of several new local, state and federal data sharing programs, 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.

2.6. Scale

This term refers to the level of detail at which information can be observed, represented, analyzed, and communicated. The development and evaluation of topographic and hydrologic databases that extend over large areas (regions) is an area 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.* [43] 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, respectively, in two 16 ha study sites in Atchison County, Missouri. Srinivasan and Engel [88], Zhang and Montgomery [44] and Mitasova *et al.* [46] 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) [22].

Numerous studies have also shown how the choice of data source and resolution can impact model predictions. Panuska *et al.* (1991) [89] and Vieux and Needham [90] quantified the effects of data structure and cell size on Agricultural Non-Point Source (AGNPS) pollution model inputs and showed how the computed flow path lengths and upslope contributing areas varied with element size. Vieux [91] examined the sensitivity of a direct surface runoff model to the effects of cell size aggregation and smoothing using different sized windows. Moore *et al.* [92] examined the sensitivity of computed slope and steady state topographic wetness index values across 22 grid spacings for three moderately large ($100km^2$) catchments in southeastern Australia. Hodgson [45] 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 [93] compared 1^o USGS

3 arc-second and 7.5' USGS 30 m DEMs and Lagacherie *et al.* [94] 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 [95] 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 [96] and Zhang and Montgomery [44] also examined the effects of DEM source scale and DEM cell spacing on the topographic wetness index and TOPMODEL watershed model predictions. Garbrecht and Martz [97] examined the impact of DEM resolution on extracted drainage properties for an 84km^2 study area 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 selected relative to the size of the smallest drainage features that are considered important for the work at hand. Bates *et al.* [98] showed how high frequency information is lost at progressively larger grid spacings.

More work of this type is required across a broad spectrum of data themes. The DEM results indicate the magnitude of this task and why only limited progress has been made with each of the original research tasks in this area listed by the UCGIS despite long-standing recognition of the implications of scale for geographic inference and decision-making. The gaps in our knowledge and lack of appropriate tools have important consequences for most of the water resource applications described in the previous section. 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 and the handling of large sets in relation to scale is likely to emerge as a critical issue in the immediate future. See Wilson *et al.* [99] for an example of the type of research required here.

2.7. Spatial Analysis in a GIS Environment

This topic is important because several of the innovations identified by the UCGIS would produce immediate benefits in the water resource application domain. Clearly, the increased availability of large, geographically referenced data sets and improved capabilities for visualization, rapid retrieval, and manipulation inside and outside of GIS will demand new methods of spatial analysis that are specifically tailored to this data rich environment (Wilkinson [73]; Gahegan) [100]. Similarly, new methods that incorporate and exploit the benefits of geostatistics are required. These methods would provide more accurate descriptions of key variables and improved diagnostics for error assessments and accuracy (uncertainty) determinations. Increased knowledge of these properties can be expected to improve the ways in which many types of environmental data are collected, stored, analyzed and visualized in the future (see Burrough *et al.* [54]; De Gruijter *et al.* [77]; and Lark and Bolam [57] for examples of soil survey applications).

Other innovations are required because many of the data sets used in the water resource applications reviewed in the previous 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 [101]; Desmet and Govers) [102]. The current options include the D8 (deterministic eight node; O'Callaghan and Mark) [103] and Rho8 (random eight node; Fairfield and Leymarie) [104] single flow algorithms, FD8 multiple flow algorithm (Freeman [105], Quinn *et al.*) [106], and the DEMON stream tube algorithm of Costa-Cabral and Burges [107]. However, this is an active area of research and more modified forms of the FD8 algorithm and a new grid-vector and grid-triangular multiple flow routing algorithms were recently proposed by Quinn *et al.* [108], Mitasova *et al.* [46] and Tarboton [109]. Additional work is now required to know which of these algorithms works best with different types of source data (square-grid DEMs, contours, GPS data sets, etc.) in specific environments (Wilson) [22]. 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 [110] 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.

2.8. The Future of the Spatial Information Infrastructure

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. The new data capture tools and advances in distributed computing noted earlier provide important new opportunities to identify gaps in existing data, collect new data, and correct errors in existing 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. The development of spatial information infrastructure can have a dramatic impact on the role which 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 buying their homes. Research will be required to identify the best approaches for customizing the same information for different users and/or purposes.

2.9. Uncertainty in Geographic Data and GIS-Based Analyses

The increased numbers of users with very different backgrounds who will be using water resource data to make important decisions, coupled with the issues raised in the previous section, elevates the importance of finding reliable methodologies for estimating, visualizing, and using uncertainty for a wide range of applications. This is important for spatial data in general, but it is especially important for water resource data where a small local change may have a dramatic impact. Several of the research projects cited earlier have tried to evaluate the uncertainty inherent in various data sets and/or analytical methods. That uncertainty exists in every phase of the geographic data life cycle, from data collection to data representation, data analyses, and final results is well known. However, our knowledge of uncertainty in geographic data and its consequences for water resource decisions made using GIS is very incomplete. More work like that of Weih and Smith [111], who traced the influence of cell slope computation algorithms through to a common forest management decision, is urgently needed in the water resource domain.

2.10. GIS and Society

This connection is obvious because our continued prosperity depends on effective water resource management. GIS can help with the collection, storage, analysis, and visualization of key information and thereby help with the development of effective water resource programs and practices. Not all water resource problems require GIS and simulation models (e.g. Lovejoy [112]; 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. The educational challenges are addressed next.

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Received on 13-04-2016 Accepted on 03-07-2016 Published on 20-03-2017

DOI: http://dx.doi.org/10.15377/2409-5710.2016.03.02.1