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Integrating GIS with hydrological modeling: practices, problems, and prospects

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Abstract

This paper reviews the practices, the problems, and the prospects of hydrological modeling based on geographic information systems (GIS). The authors argue that current stand-alone and various loose/tight coupling approaches for integrating GIS with hydrological modeling are essentially technology-driven without adequately addressing the conceptual problems involved in the integration. The conceptualizations of space and time embedded in the current generation of GIS are not conceptually compatible with those in the hydrological models. This incompatibility implicitly imposes constraints on the type of hydrological models that can be developed. By reframing the future research agenda from the emerging geographic information science (GIScience) perspective, the authors contend that the integration of hydrological modeling with GIS should proceed with the development of a high-level common ontology that is compatible with both GIS and hydrological models. The new ontological scheme should incorporate alternative conceptualizations of space and time capable of handling cross-scale linkages of hydrological processes. The emerging interoperable paradigm should be the core strategy for the implementation of the new framework. This paper also calls for more research to better handle and communicate the uncertainties in the process of GIScience-based hydrological modeling. GIScience-based hydrological modeling will not only espouse new computational models and implementation strategies that are computing-platform-independent but also liberate us from the constraints of existing hydrological models and the rigid spatial–temporal framework embedded in the current generation of GIS, and enable us to advance hydrological sciences, develop more versatile GIS technologies, and seek innovative applications relevant to societal concerns. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

For almost two decades in the 1960s and 1970s, geographic information systems (GIS) and hydrological modeling developed in parallel with few interactions. Major research efforts toward the integration of GIS with hydrological modeling did not take place until the late 1980s, as a part of the GIS community's efforts to improve the analytical capabilities of GIS (Fotheringham & Rogerson, 1994; Goodchild, Haining, & Wise, 1992) and hydrologists' new demand for accurate digital representations of the terrain (Clark, 1998; Singh & Fiorentino, 1996). Nowadays, both GIS users and hydrologists have increasingly recognized the mutual benefits of such an integration from the successes of the past 10 years. Various hydrological modeling techniques have enabled GIS users to go beyond the data inventory and management stage to conduct sophisticated modeling and simulation. For hydrological modeling efforts, GIS, especially through their powerful capabilities to process DEM (Digital Elevation Models) data, have provided modelers with new platforms for data management and visualization. The rapid diffusion of GIS in society has the potential to make various hydrological models more transparent and enable the communication of their operations and results to a large group of users. The growing literature on the integration of GIS with hydrological modeling attests the recognition of such mutual benefits (DeVantier & Feldman, 1993; Maidment, 1993, 1996; McDonnell, 1996; Moore, 1996)

In this paper, we aim to achieve three goals:

1. to review the current practices of GIS-based hydrological modeling;
2. to identify the existing problems of current efforts to link GIS with hydrological modeling;
3. to discuss a new research agenda from the emerging geographic information science (GIScience) perspective.

This paper is organized into five sections. In the next section, the current practices of GIS-based hydrological modeling are reviewed. Then, the existing problems of coupling GIS with hydrological modeling are discussed, followed by a look at the future prospects of hydrological modeling from the perspective of GIScience and, finally, concluding remarks.

2. Current practices

The lack of sophisticated analytical and modeling capabilities was recognized by GIS researchers and hydrologists alike as one of the major deficiencies of GIS technology (Maidment, 1993; Wilson, 1996). Several research initiatives in North America and Europe have focused on the improvement of spatial analytical and modeling capabilities of GIS technology during the past 10 years (Goodchild et al., 1992). The integration of GIS with hydrological modeling was part of these broad research efforts to link spatial analysis and modeling with GIS. Although overlapping with many other GIS modeling efforts in terms of the general methodology

(Sui, 1998), the integration of GIS with hydrological modeling has a set of different issues from other kinds of GIS-based environmental modeling (Goodchild, Parks, & Steyaert, 1993, 1996; Karimi & Houston, 1996). For example, unlike most other kinds of environmental modeling, hydrological modeling has a set of well-established practices and standards widely accepted by hydrologists and hydraulic engineers, and modeling results sometimes are used for regulatory purposes. Current practices of integrating GIS with hydrological modeling thus deserve a separate scrutiny.

Generally speaking, four different approaches have been widely used to integrate GIS with hydrological modeling (Fig. 1). Our discussions here are confined to methodological issues with an emphasis on surface hydrological modeling. Those interested in the details of specific models are referred to several other comprehensive reviews (DeVries & Hromadka, 1993; Gupta, Woodside, Raykhman, & Connolly, 1996; Singh & Fiorentino, 1996).

2.1. Embedding GIS-like functionalities into hydrological modeling packages

This approach aims to embed GIS functionalities in hydrological modeling packages, and has been adopted primarily by hydrological modelers who think of GIS essentially as a mapping tool and conceptually irrelevant to the fundamentals of hydrological modeling. This approach usually gives system developers maximum freedom for system design. Implementation is not constrained by any existing GIS data structures, and usually this approach is capable of incorporating the latest development in hydrological modeling. The downside of this approach is that the

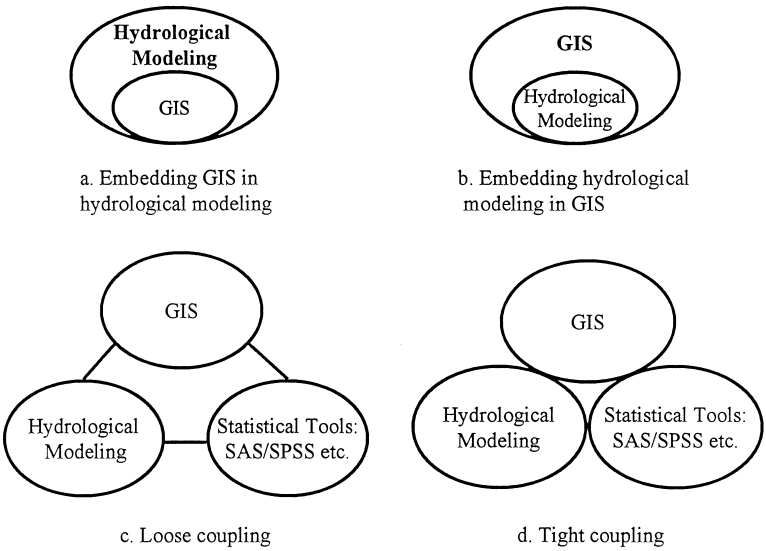

Fig. 1. Integrating GIS with hydrological modeling: current practices.

data management and visualization capabilities of these hydrological modeling software packages are in no way comparable to those available in commercial GIS software packages, and programming efforts also tend to be intensive and sometimes redundant. The developers of the latest version of RiverCAD, HEC-RAS 2.0, RiverTools, and MODFLOW have basically taken this approach.

2.2. Embedding hydrological modeling into GIS packages

A few leading GIS software vendors in recent years have made extra efforts to improve the analytical and modeling capabilities of their products. Pioneered by HEC-SAS developed by the Army Corps of Engineers (Davis, 1978), several commercial software vendors have developed stand-alone GIS modules with functions that can be used for a variety of hydrological modeling needs. Certain hydrological modeling functions have been embedded in leading generic GIS software packages such as ESRI's ArcStorm and ArcGrid, Integraph's InRoads, etc. This approach builds on top of a commercial GIS software package and takes full advantage of built-in GIS functionalities, but the modeling capabilities are usually simplistic and calibrations must take place outside of the package. Also, these models tend not to be industry standard and/or have not been validated.

2.3. Loose coupling

This approach usually involves a standard GIS package (e.g., Arc/Info) and hydrological/hydraulic modeling programs (HEC-1, HEC-2, STORM, etc.) or a statistical package (e.g., SAS or SPSS). Hydrological modeling and GIS are integrated, via data exchange using either ASCII or binary data format, among several different software packages without a common user interface. The advantage of this approach is that redundant programming can be avoided, but the data conversion between different packages can be tedious and error prone. Because computer programming is minimal, this approach may be the most realistic method for most GIS users and hydrological/hydraulic engineers to conduct modeling work.

2.4. Tight coupling

This approach embeds certain hydrological models within a commercial GIS software package via either GIS macro or conventional programming. With the recognition of the users' need to develop customized applications, more and more GIS software vendors are providing macro and script programming capabilities (such as ESRI's Avenue and AML) so that users can lump a series of individual commands in a batch mode or develop a customized user interface for specific applications. But such languages are seldom powerful enough to implement sophisticated models. An alternative method is to incorporate user-written routines into a GIS. Several software packages have already developed mechanisms to allow user-developed modeling libraries or routines to be called within the normal pull-down menu of a particular software package. This approach, however, requires

a well-defined interface to the data structures held by the GIS. The challenge will be to develop new mechanisms for all users to access spatial data without needing to know about the particular data structures used in the GIS (Goodchild et al., 1992).

These four general approaches have resulted in abundant empirical studies in various regions in the world, most of which rely on a combination of loose- and tight-coupling. These studies reported in the literature range from simple data preprocessing and hydrological parameter estimation (Bhaskar, Wesley, & Devulapalli, 1992; Shumann, 1993; Smith & Vidmar, 1994) to testing the validity of distributed hydrological models (Beven & Moore, 1992; De Roo, Wesseling, & Van Deursen, 1998; Johnson & Miller, 1997), from using GIS merely as mapping and visualization tools (Shamsi, 1996) to comprehensive hydrological storm water modeling and management (Kwadijk & Sprokkereef, 1998). The study areas range from the world's most densely populated cities in Asia (Brimicombe & Bartlett, 1996) to rural areas in Africa (Corbett & Carter, 1997); from the Swiss flat agricultural land (Consuegra, Joerin, & Vitalini, 1995) to Alberta's Rockies foothill in Canada (Muzik & Pomery, 1990). These studies have also covered the entire continuum of geographical scales from a local watershed (James & Hewitt, 1993; Jeton & Smith, 1993) to regional water resource planning (Abrahart, Kirby, & McMahon, 1994; Lanza & Siccardi, 1995; Schultz, 1994) to continental and global water balance and air circulation models (Oki, Musiake, Matsuyama, & Masuda, 1995). The specific topics covered include surface run-off estimation (Julien, Saghafian, & Ogden, 1995; Stuebe & Johnston, 1990), flood-risk assessments and hydrological drainage modeling (Milne & Buchanan, 1991; Shamsi & Fletcher, 1994; Shea, Grayman, Darden, Males, & Sushinsky, 1993), non-point pollution and water quality studies (Kao, 1992; Mitchell, Engel, Srinivasan, & Wang, 1993), economic and hydrologic interdependence (Ward & Lynch, 1996), and subsurface ground water modeling (Richards, Raaza, & Raaza, 1993), etc. Although ESRI's Arc/Info and the US Army Corps of Engineers's HEC series dominated these modeling works, a variety of other GIS and modeling software tools have also been used, such as INTEGRAPH's InRoads, GRASS and TOPMODEL (Chariat & Delleur, 1993; Moeller, 1991; Warwick & Haness, 1992), IDRISI, AutoCAD (Cline, Molinas, & Julien, 1989), SPUR model (Sasowsky & Gardner, 1991), SPANs, and STELLA (McDonnell & Macmillan, 1993). Several studies have also indicated that remote sensing and GPS (Global Positioning Systems) play an increasingly important role in these endeavors (Costa-Cabral & Burges, 1993).

3. Existing problems

It is generally agreed that the integration of GIS with hydrological modeling has enabled GIS users to go beyond data management and thematic mapping to conduct sophisticated analysis and simulation for both scientific research and policy analysis. GIS provided hydrologists and hydraulic engineers with the ideal computing platform for data inventory, parameter estimation, mapping and visualizing

results for hydrological/hydraulic modeling, thus greatly facilitating the design, calibration, and implementation of various hydrological/hydraulic models. However, we should not let the fancy maps and graphics of GIS blind us from the real issues in hydrological modeling. The current practices are dominated by technical concerns without adequately addressing some of the important conceptual issues involved in the integration of GIS with hydrological modeling. While the technical problems related to the database integration are well documented (Adam & Gangopadhyay, 1997; Buogo & Chevallier, 1995), few papers in the literature have discussed the broad conceptual issues involved in the integration of GIS with hydrological modeling. We believe that there are problems in both hydrological models and the current generation of GIS. These problems must be addressed before we can make the integration of GIS with hydrological modeling theoretically consistent, scientifically rigorous, and technologically interoperable.

3.1. Problems of hydrological modeling

According to Chow, Maidment, and Mays (1988), hydrological models can be classified according to their conceptualizations and assumptions of three key parameters—randomness, space, and time. Depending on how randomness, space, and time are conceptualized, we can have eight different kinds of models in general (Fig. 2). The models widely used in the current practices of GIS-based hydrological modeling are dominated by deterministic lumped models because of the availability of various modeling packages such as the US Army Corps of Engineers' HEC-1 and HEC-2, the US Soil and Conservation Service's TR-20 and TR-40, USDA's SWAT, DoT's WSPRO, EPA's WASP and HSPF, and USGS's DRM3 and PRMS, etc. Although these hydrological modeling packages have been widely adopted by government agencies and the private sector, we should be well aware of the fact that their loose coupling with GIS does not improve the scientific foundation of these models or put hydrological modeling onto a firmer foundation as some naive practitioners tend to believe (Grayson, Bloschl, Barling, & Moore, 1993). We need to re-evaluate the fundamental assumptions and simplifications in these models and re-examine their validity. Several researchers have challenged the foundations of these models (Grayson, Moore, & McMahon, 1992; Smith & Goodrich, 1996) and many researchers have been active to develop spatially distributed and stochastic models (Beven & Moore, 1992; Romanowicz, Beven, & Moore, 1993; Wheater, Jakeman, & Beven, 1995). However, these newly developed models are still mostly confined to research laboratories and not widely used in practice. Obviously, our primary objective should not only focus on doing the thing right in the technical sense but also, perhaps more importantly, challenge whether it is the right thing to do in the scientific sense.

3.2. Problems of GIS

With its historical roots in computer cartography and digital image processing, the development of GIS to date has relied upon a limited map metaphor (Burrough &

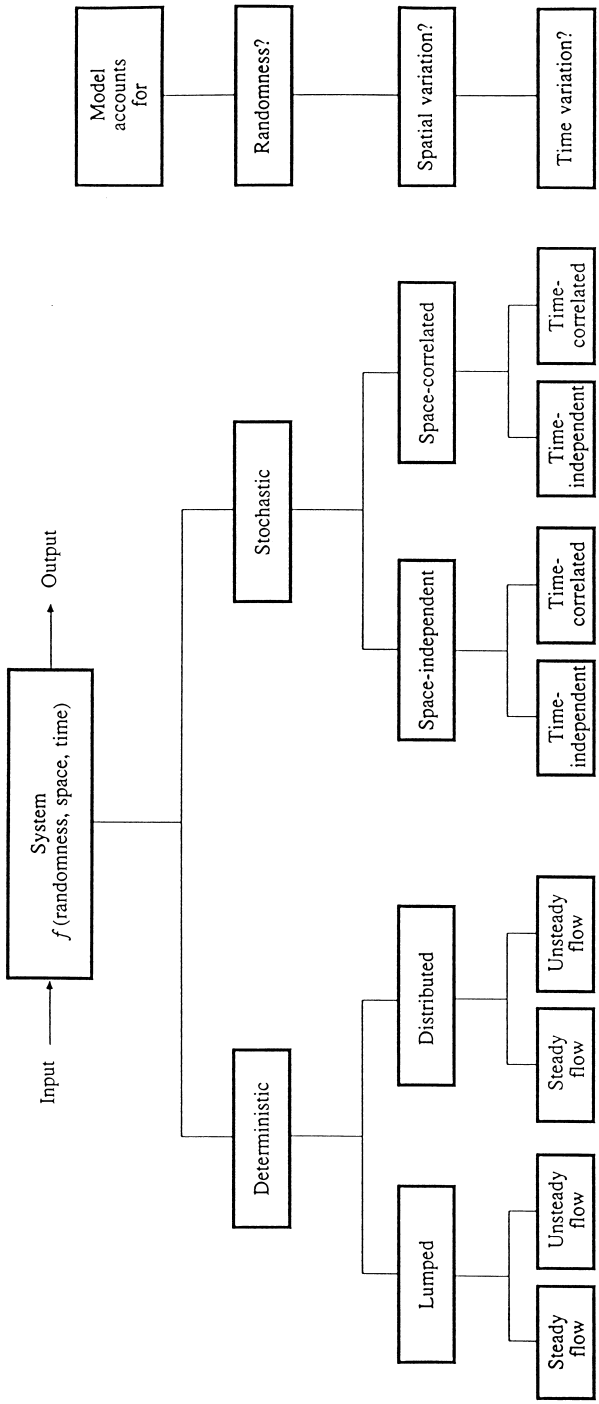

Fig. 2. A taxonomy of hydrological models (after Chow et al., 1988).

Frank, 1995). Consequently, the representation schemes and analytical functionalities in GIS are geared toward map layers and geometric transformations. The layer approach implicitly forces a segmentation of geographic features (Raper & Livingstone, 1995). This representation scheme is not only temporally fixed but is also incapable of handling overlapping features (Hazelton, Leahy, & Williamson, 1992). Perhaps more importantly, as so many GIS theorists have pointed out, underneath this crude map metaphor in the current generation of GIS is an implicit conceptualization of absolute space based upon Newtonian mechanics (Gatrell, 1991). The absolute conceptualization of space has forced space into a geometrically indexed representation scheme via planar enforcement, and time is conceptualized as discrete slices. In contrast, depending on how randomness is handled, space and time in hydrological models can be conceptualized quite differently. For example, stochastic models represent variables as a random field—a region of space and time within which the value of the variable at each point is defined by a probability distribution. The Euclidean geometry-based representation of space built into commercially available GIS software packages, either as an inert assembly of polygons or as a lattice of raster cells, is ill-structured to represent random fields. Also, the limited capabilities of handling flow data in the current generation of GIS is based upon Dijkstra's algorithm for traffic flow routing. Dijkstra's algorithm takes the Lagrangian view of motion (focusing on a moving object) whereas hydrological flow modeling usually assumes the Eulerian view of motion (focusing on a fixed frame in space through which the motion occurs). These different conceptualizations of motion also make GIS difficult to model hydrological flows (Maidment, 1993). Although technically we can plug in various hydrological models into GIS through the strategies outlined in the previous section, GIS and hydrological models are just used together, not really integrated because of the fundamentally different spatial data representation schemes involved (Abel, Kilby, & Davis, 1994). Therefore, in order to accomplish the seamless integration of GIS and hydrological models, we need to conduct research at a higher level, that is to develop and incorporate novel approaches to conceptualizing space and time that is interoperable both within GIS and hydrological models.

Obviously, the current practices of integrating GIS and hydrological modeling are essentially technical in nature and have not touched upon the more fundamental issues in either hydrological models or GIS. We have succeeded only in putting old wine in new bottles—an improved means for unimproved ends. Simply being able to run a HEC-1 or HEC-2 model in Arc/Info or a CAD system improves neither the theoretical foundation nor the performance of the model. GIS-based hydrological modeling has resulted in a tremendous amount of representational compromise (Gan, Dlamini, & Biftu, 1997). Such problems call for a fresh look at the integration of GIS with hydrological modeling. We must think above and beyond the technical domain on this issue. Instead of being dictated by GIS technology, the emerging GIScience itself should drive the next round of GIS-based hydrological modeling efforts. Although the final resolution of these technical, conceptual, and implementation issues may still take some time, the first useful step may be to lay out a broadly conceived research agenda.

4. GIScience-based hydrological modeling: future prospects

Problems in the current practices of GIS-based hydrological modeling cannot be resolved if we continue to treat the integration of GIS with hydrological modeling as essentially a technical issue. Instead, we must challenge the implicit assumptions behind hydrological models and GIS, and shift our research efforts to more fundamental issues in conceiving and representing the hydrological processes in the appropriate spatial–temporal framework. We need to elevate our research efforts to a higher conceptual level. To avoid being trapped in the narrowly defined technical issues, we believe that the emerging GIScience is immensely useful in formulating our future research agenda. To set up the context for GIScience-based hydrological modeling, it would be instructive to take a quick look at the core elements of GIScience.

4.1. Elements of GIScience

Since Goodchild (1992) first raised the banner of a new discipline called geographic information science, the GIS community has increasingly recognized the importance of transcending the limits of GIS technology to focus on the more generic issues in spatial data handling. During the past 5 years, the GIS community has responded enthusiastically to Goodchild's call, as evidenced by the establishment of the new university consortium of GIScience in the USA, the development of the new on-line GIScience curriculum, and the publication of several new journals in GIScience. Although still in its infancy and the disciplinary status may be debatable (Pickles, 1997; Wright, Goodchild, & Proctor, 1997), the three core elements of a GIScience, as articulated in the NCGIA proposal, are crucial for a research agenda on GIScience-based hydrological modeling (NCGIA, 1996). These three core elements in GIScience are as follows:

1. *New models of geographic concepts*. The NCGIA contends that our understanding of key geographic concepts and their appropriate representations is currently incomplete. The first area GIScience should investigate is how key geographic concepts such as space and time have been conceptualized by different people and different disciplines. As ease of use is increasingly important in the Information Age, studies on fundamental geographic concepts will be critical for us to better understand the geographic world around us. While the conceptualization of space in the current generation of GIS according to rigid Euclidean geometry may work well for land parcel data and political boundaries, the same conceptual scheme may be very problematic for dealing with hydrological space because of its fluidity. It is widely regarded as one of the most fundamental issues in GIScience to develop new models of basic geographic concepts such as space, place, and scale.
2. *Computational implementations of geographic concepts*. This area concentrates on building new computational models of geographic spaces and the social and environmental processes that operate in them. Exploring the best

computational strategy for the implementation of various conceptualizations of space is to achieve interoperability among different computational models. This area of GIScience is growing very rapidly and coincides with the development of geocomputation (Karimi & Blais, 1996; Longley, 1998; Macmillan, 1998; Mann, 1997).

3. *Geographies of the Information Society*. This element focuses on the positive and negative impacts of technology on individuals, organizations, and society. This branch of GIScience examines what kinds of new spatial relationships are emerging in the new Information Society and what the societal impacts are by introducing GIS into various facets of our social practices.

While GIScience is still unfolding and by no means carved in stone, these three core areas in GIScience provide us a broad guideline for the future research of GIScience-based hydrological modeling. It is our opinion that the success of GIScience-based hydrological modeling will depend upon how successfully we have developed new conceptualizations of space and time that are compatible and consistent with both the new hydrological models and GIS technology, their efficient/interoperable implementations on various new computing platforms, and the exploration of new ways of handling and communicating uncertainties in application areas of great societal concerns.

4.2. GIScience-based hydrological modeling

Both GIS users and hydrologists have recognized that the different conceptualization of space, time, and randomness in GIS and hydrological models poses a major limit toward the integration of GIS with hydrological modeling (Maidment, 1993; Browne, 1995). In a fully integrated system, the data should be located in the same database and be accessible by both the models and the GIS functions (Raper & Livingstone, 1995). This means we must identify a new conceptual scheme that possesses rich semantics capable of representing a coherent spatial–temporal framework consistent with both GIS and hydrological models. The foundation of this new framework must start with a common ontology for both GIS and hydrological models. The development of a generic hydrological data exchange format (Djokic, Coates, & Ball, 1995) will be unlikely to succeed without a higher level common ontology.

4.2.1. A common ontology for GIS and hydrological models

Ontology deals with the nature of being and it has played an increasingly important role in information system design and development (Guarino, 1998). An ontology of geographic kinds is designed to gain better understanding of the forms and the processes of the geographic world, and to support the development of GIS that is conceptually sound (Smith & Mark, 1998). The common ontology for a GIScience-based hydrological model begins with the exploration of alternative spatial–temporal frameworks. The rigid spatial–temporal framework embedded in the current generation of GIS is too restrictive to capture the complex hydrological

reality. The next generation of GIS should incorporate multiple dimensions of space and time in order to become a flexible platform to implement hydrological models. The alternative conceptualization of space and time in GIS that is compatible with hydrological models will be one of the most important cornerstones for the successful integration of GIS with hydrological modeling.

Currently, there exists a dichotomy of the so-called field versus object view of geographic reality in GIS. Reality is conceptualized either as continuous fields represented by various kinds of spatial tessellation or as discrete objects represented by points, lines, and polygons (Kemp, 1997; Peuquet, 1988). As of now, little research has been done to explore consequences of these dichotomous conceptualizations in hydrological modeling. We also do not know whether there exists alternative conceptualizations besides these two.

Both the field and the object view embodies the Newtonian absolute view of space which treats space as an empty container, independent of the objects within. Whereas the Leibnizian (relative) view of space contends that space and substances are inseparable, and space is primarily defined by the interrelationships among the objects. As implemented in two new hydrological modeling packages—HEC-RMS (available: www.hrc-hec.usace.army.mil) and RiverWare (available: cadsweb.colorad.edu)—could the Leibnizian relative view of space be an alternative for both GIS and hydrological models?

Although time is an explicit element in most hydrological models, the representation of time in GIS is almost non-existent in the current generation of GIS. Although many researchers have devoted their research efforts toward incorporating the temporal element in GIS (Langran, 1992; Peuquet, 1994), time is still not an integral part of the GIS data model yet. Similar to space, time can also be conceptualized by dramatically different structures. For example, time can be either conceptualized as a discrete or a continuous variable; time may be linearly or partially ordered or may form a temporal cycle exhibiting periodicities; or time may be associated with time points, intervals (durations) or disjoint unions of time intervals (Worboys, 1995).

Besides space and time, we believe that scale should also be an integral element of this common ontology. Although the impacts of scales and grid sizes on the modeling results have been widely discussed (Feddes, 1995; Garbrecht & Martz, 1994; Kalma & Sivapalan, 1995; Moore, Lewis, & Gallant, 1993; Zhang & Montgomery, 1994), the interaction among local, regional, and global processes is still poorly understood. The establishment of multiple scale representations and cross-scale linkages in the common ontology will greatly enhance the robustness of hydrological modeling and facilitate our understanding of climate, surface, and ground water interactions.

These alternative views of space and time with explicit consideration of scale will be useful in defining a common ontology for GIScience-based hydrological modeling. So far GIS is based upon a Newtonian absolute representation of space coupled with the crude conception of linear time slicing. GIScience-based hydrological modeling should explore the new dimensions of space and time, and take a holistic approach about the multidimensionality of space and time in order to more

realistically capture the hydrological dynamics. What is equally challenging is how to operationalize the alternative, holistic conceptualization of space–time to replace the current Cartesian/Newtonian concept of space and time. The alternative representation scheme for space–time will not only lay a new conceptual foundation for GIS technology, but also stimulate innovative applications. The work by Robinson and Mackay (1996) to model the semantics of GIS-based modeling is an important step along this direction.

4.2.2. Computational implementation strategies

The success of the common ontological framework for GIScience-based hydrological modeling will hinge on its effective implementation according to the concept of interoperability. The interoperable paradigm aims to develop software products across distributed computing platforms according to the concept of the Open Geodata Interoperability Specification (OGIS; Buehler & McKee, 1996). The concept of OGIS and interoperability has already stimulated new software development trends in the industry, and is also gaining attention among academic researchers (Goodchild & Egenhofer, 1998). Instead of developing a fully integrated GIS, software vendors and researchers are exploring new ways of developing a much leaner core module with numerous more task specific, embeddable modules. These object-oriented, embeddable modules can not only be easily integrated into a core GIS package but also be seamlessly integrated with other application programs, such a hydrological modeling package. In addition, with explosive growth of both the Internet and Intranets, the development of Web-based software tools is necessary so that whoever has access to the Internet can run the program regardless of the computing platform and the location of the user. ESRI's MapObjects, the spatial data engine, and the new map server on the World Wide Web are important steps toward full interoperability. New platform-independent software such as JAVA provides us with the potential to seamlessly integrate GIS with hydrological modeling.

The interoperability of GIScience-based hydrological modeling demands a higher level of agreement in our basic data models. Thus a common ontology is a prerequisite for the success of interoperable GIScience-based hydrological modeling. Similar to the future of interoperable GIS (Goodchild & Egenhofer, 1998), we envision that the future of hydrological modeling will eventually become:

1. *distributed*, with processing, storage of data, and user interaction occurring at locations that are widely scattered at different geographic locations;
2. *disaggregated*, with plug and play components from different vendors that are designed to interoperate through a common ontological framework;
3. *decoupled*, with disaggregated components needed to complete a given task being distributed over many networked systems.

Pioneering works toward these interoperable 3-D (distributed, disaggregated, decoupled) goals include (but are by no means limited to) the efforts of Maxwell and Costanza (1995) to develop distributed modular spatial ecosystems modeling, the dynamic modeling language of Wesseling, Karssenberg, Burrough, and Van

Deursen (1996) to link GIS and environmental modeling, and Mar's interoperable GIS for spatial process modeling (Mar, Pascoe, & Benwell, 1997).

4.2.3. Handling and communicating uncertainties

If we succeed in developing GIScience-based hydrological modeling interoperable across computing platforms, hydrological modeling will be more widely accessed and used to address water-related issues of great societal concerns. Robust hydrological modeling will be an integral part of management tools for sustainable watershed development. The interoperable GIScience-based hydrological model will also greatly empower citizens and communities in flood-prone areas to play an important role in flooding control, flood mitigation, floodplain mapping, and flood insurance studies. However, as we discussed elsewhere (Sui & Maggio, 1998), every single step in the process of integrating GIS with hydrological modeling is full of uncertainties, ranging from data acquisition, to model calibration, to results visualization. Currently, we still lack effective methods to handle and communicate these uncertainties and we believe more research is needed (Heuvelink, 1998; Tung, 1996; Kundzewicz, 1995).

We agree with Openshaw's statement that we may never completely eliminate uncertainties inherent in spatial databases and spatial modeling processes, but we can find better ways to live with them (Openshaw, 1989). We propose a two-pronged approach to deal with the uncertainty issues. First, we should explore the possibility to develop a synergistic analytical method to handle uncertainties. Existing uncertainty measures are dominated by statistical measures and are unable to address the uncertainties due to imprecision and incompleteness. Although probabilistic methods excel in dealing with uncertainties due to randomness, Bayesian probability methods are less useful in handling uncertainties introduced by incomplete information or inherent impressions. Recent advances in uncertainty research have demonstrated the great potential of two alternative methods—Dempster-Schafer's evidence theory (to deal with uncertainties due to incompleteness) and Lotfi Zadeh's fuzzy set theory (to deal with uncertainties due to imprecision). Empirical studies indicated that evidence theoretic and fuzzy set approaches are complementary to traditional Bayesian statistical approaches to address the uncertainty issue (Goodchild, Buttenfield, & Wood, 1994; Stoms, 1987; Worboys, 1998). It is beyond the scope of this paper to review the details of these two theories and how they may be applied to quantify uncertainties. Yet we believe that a new approach through the synergy of Bayesian, Dempster-Schafer, and fuzzy set-theoretic approaches will provide us with better ways to analytically handle these uncertainties due to randomness, imprecision, and incompleteness. We envisage that a new analytical method based upon the integration of Bayesian statistics, Dempster-Schafer evidence theory, and fuzzy set theory may provide us with the most effective way of dealing with all the uncertainties in the floodplain mapping process.

Second, we need to explore new methods of communicating results of uncertainty measures. Both visual and non-visual methods of communicating uncertainties are worth exploring. It has long been recognized by the GIS community that the ability to communicate to users the uncertainty of the digital databases is a critical step in

maintaining professional integrity in applications of great societal concerns such as floodplain mapping, flood insurance rating, and watershed development planing (Clark, 1996; Hwang, Karimi, & Byun, 1998; Klinkenberg & Joy, 1994). Although there exists no general agreement or professional protocols, we believe that the methods of communicating uncertainties of spatial databases reviewed by Hunter and Goodchild (1996) can be applied to convey the uncertainties of integrating GIS with hydrological modeling. Several visual methods can be deployed to represent these uncertainties. For example, instead of using crisp lines to show various floodplain boundaries, we can use the Perkal Epsilon band method to show a graduate transitional zone for floodplain boundaries (Goodchild, 1991). Various other cartographic techniques such as shape, color, tone, texture, and even cartographic animation can be used to graphically illustrate the uncertainties. Other alternative methods, such as aural tools, multimedia approaches, the use of the World Wide Web, and virtual reality are also being investigated for communicating uncertainties of spatial databases (Fisher, 1994). With the increasing use of GIS and digital databases in the floodplain mapping and management processes, these alternative approaches may also lend a helpful hand for us to better communicate uncertainties to a wide range of users.

5. Concluding remarks

This paper has reviewed the practices, the problems, and the prospects of GIS-based hydrological modeling. Although we have seen some technical progress during the past 10 years, the integration of GIS with hydrological modeling is essentially technology-driven without challenging the suitability of the spatial–temporal framework embedded in the current generation GIS. By reframing the future research agenda from a GIScience perspective, we contend that the integration of hydrological modeling with GIS should proceed with the development of a high-level common ontology that is compatible with both GIS and hydrological models. The common ontological framework should incorporate multi-dimensional concepts of space, time, and scale. The implementation of the new ontological framework should follow the protocols of the emerging interoperable paradigm. GIScience-based hydrological modeling will not only equip us with new computational models and implementation strategies that are interoperable and embeddable across computing platforms, but also liberate us from the constraints of existing hydrological models and the rigid spatial–temporal framework embedded in the current generation of GIS. This paradigm shift in coupling GIS with hydrological modeling will enable us to think above and beyond the technical issues that have occupied us during the past 10 years. The interoperable GIScience-based hydrological modeling will also lead to a wide-range of applications with easy access. This paper also calls for more future research efforts on handling and communicating uncertainties in the process of integrating GIS with hydrological modeling. Understanding these uncertainties is a major step forward to better fulfilling the social role of hydro-GIS in its wide-range applications.

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