# A STATE-OF-THE-ART REVIEW OF INTERFACING GIS WITH WATER RESOURCE MODELS

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ABSTRACT: In an effort to simultaneously analyse spatial and temporal phenomena, two unique, independently developed technologies—geographic information systems (GIS) and predictive water resource models—are being interfaced with varying degrees of sophistication. There are numerous ways to integrate GIS with water resource models because neither technology was intended designed to work together. The creation of application "suites" for the evaluation and visualisation of engineering challenges has also been aided by ongoing model improvements and the advancement of graphical user interfaces (GUIs). A universal interface strategy cannot currently be used due to differences in spatial sizes, data accessibility, modelling programme choices, and computer resource availability. This article offers a state-of-the-art critical analysis of recent developments in the integration of GIS with models of forecast water resource availability. Discussions of the constraints on effective interface design and potential future directions—including suggestions for resolving many current difficulties—are given priority.

(KEY TERMS: geographic information systems (GIS); modeling; surface water hydrology; water quality; water resources; simula- tion.)

## INTRODUCTION

Accurate and effective information evaluation is essential to finding solutions to today's complicated water resource problems. Yet, using tools for quick interpretation is necessary to extract the information from multiple data gathering and modelling efforts in such diverse fields as geography, geology, engineering, meteorology, and sociology. For many science and engineering disciplines, GIS has emerged as a popular spatial analysis, interpretation, and display approach. GIS is also acknowledged as a developing and useful technology for water resource specialists. Decision support systems (DSS), which use databases, GIS, and predictive models to help solve complex science and engineering problems, are still being developed.

While being widely used, GIS technology wasn't created with engineering modelling applications in mind; instead, it was created as a general tool to store, retrieve, edit, analyse, and map geographic data. Due to these antecedents, modern commercial GIS software focuses heavily on spatial position and object properties (Miles and Ho, 1999). However, the spread of GIS technology to a wider variety of model users, researchers, and developers has been made possible by the ongoing drop in computer technology costs and the concurrent growth in processing speeds. The planning, design, analysis, operation, and maintenance of water and sewer systems in urban areas (McKinney et al., 1992); the evaluation of nitrate contamination in ground water (Lasserre et al., 1999); and the incorporation of sophisticated hydrodynamic and water quality models within a GIS framework for analysis of inland waterway contaminant spills are examples of applications in the field of water resources (Martin et al., 2004). This expansion of uses has given rise to new issues that confront academics and their research goals more than it does developers of spatial analytic tools.

This review examines previous and current interfacing strategies between water resource models and GIS systems. It illustrates the diversity of approaches, with an emphasis on critically exploring the present state of the art and providing insights and recommendations to those considering undertaking interfacing exercises.

The review begins with a discussion of the motivations for incorporating GIS as a tool in water resource modeling. Discussion of the use of pre-processor and post-processor graphical user interfaces (GUIs) and the state of water resource modeling follows. Selected interfacing efforts, representing ground water, non-point source pollution, watershed, hydrologic, and surface water models are then reviewed. Issues affecting interface strategy and challenges typically encountered are further explored in conjunction with outlining possible difficulties and errors when excessive reliance is placed on a GIS system. Suggested future directions for water resource modeling efforts utilizing GIS conclude the discussion.

## MOTIVATIONS FOR EMPLOYING GIS WITHIN WATER RESOURCE MODELS

For water resources engineering problem solving, GIS offers a cognitive spatial representation of complex hydrologic and hydraulic systems. GIS is capable of incorporating related spatial data into traditional water resources databases in order to present a more comprehensive view of the target region. This inte- grated view is developed by combining sociologic, geo- graphic, geologic, and environmental factors related to the spatial entities of the water resource problem and availing them for use in the decision making pro- cess (Csillag, 1996). Of specific interest to decision makers is the capability of GIS to visually display information for interpretation of water resource model inputs and outputs, which enables users to take a more dynamic approach with data input, modi-fication, scenario development, and evaluation.

Based on the array of GIS applications and users, significant benefits may result from coupling GIS to predictive models. Bennett indicates that GIS offers a virtual environment within which decision makers and scientists can explore theory and evaluate com- peting management strategies. Miles and Ho (1999) counter this view by noting that GIS has yet to reach this lofty plateau as current generation GIS provides a mediocre modeling environment at best. However, commercial GIS does offer the ability to handle sever- al forms of spatial data, perform limited spatial

analysis, and produce acceptable cartographic output (Dangermond, 1993). GIS software remains exclusive in its ability to capture and manage spatially refer- enced data such as points, lines, and polygons (vector data model) or as continuous fields (raster data model).

Within the vector structure, geographic features and objects are represented by points, lines, and poly- gons with specific coordinates in continuous map space, similar to traditional hard copy maps that identify landmarks, buildings, roads, streams, water bodies, and other features by points, lines, and shaded areas (Garbrecht *et al.*, 2001). Additionally, each object in the vector structure includes topologic infor- mation describing its spatial relation to neighboring objects, specifically its connectivity and adjacency. This fixed definition of, and linkage between, objects makes vector structures attractive and allows for automated analysis and interpretation of spatial data in GIS environments (Meijerink *et al.*, 1994).

Alternatively, raster structures divide space into a two-dimensional grid of cells, similar to a spread- sheet, where each cell contains a representative value of the attribute being mapped. Row and column val- ues, with the boundary of the grid registered to benchmark spatial coordinates, references each grid cell. A point is represented by a single grid cell, a line by a string of connected cells, and areas by groups of adjacent cells (Garbrecht *et al.*, 2001). The simplicity of raster structure data processing and the volume of readily available remotely sensed data in raster for- mat contribute to its popularity with GIS users.

If developed for use as a spatial database, GIS assists modeling applications by handling unique forms of data that are either incompatible with or dif- ficult to store in an aspatial database. Prior to pos- sessing the capability to process large volumes of spatial data, engineers commonly employed gross abstractions and assumptions or modeled on a site specific basis (Miles and Ho, 1999; Vieux, 2001). The development of relational database features within GIS software has enabled an increased level of data consistency and integrity between applications. GUI and query languages permit rapid selection and modi-fication of attribute data and parameter values, allow-ing for swift sensitivity analyses and multiple scheme evaluation. It should be noted that GIS is not limited to serving as a database for parameter or attribute data. Qualitative and quantitative data may be inte- grated through spatial relationships rather than through attribute relationships that may not exist (Frost *et al.*, 1997). This is accomplished by employing the overlay function of GIS where multiple maps are visually or topologically combined, allowing for rapid data visualization and model output verification.

The most noticeable benefit of employing GIS is the ability to readily produce high quality maps incorpo- rating both model output and geographic entities, fur- ther enabling visual support during decision making processes. Additional analyses and interpretations may be exercised by exploiting the supplementary spatial analysis features of GIS (e.g., slope, direction, area). By employing interactive and interpretive visu-alization of GIS-based model results, rapid assess- ments of input data legitimacy, consistency, and correlation with outputs may be made.

Areas of potential concern where more rigorous analysis is required may be readily identified through the use of visual analysis. Spatial operations of GIS not only supplement traditional map-based modeling but serve to eliminate “paper-based” map manipula- tion. Common operations such as area computation, flow path length measurement, and nearest distance determination (through Euclidean or network space) can be used to conveniently derive model dependent parameters (Singh and Fiorentino, 1996; Miles and Ho, 1999; Gurnell and Montgomery, 2000; Vieux, 2001; Shamsi, 2002). As such, with increasing com- puter processing speeds and more advanced integra- tion software, the ability of GIS to continually update itself by reoverlaying data onto a base map illustrates the potential for dynamic analyses of water resource planning and scenario evaluations.

## GIS AND MODEL INTERFACING

This review notes a number of water resource mod- eling efforts rather than focusing more broadly on environmental or spatial modeling. As noted by Hartkamp *et al.* (1999), the term “environmental modeling” encompasses techniques ranging from remote sensing and image generation/interpretation to the use of models for meteorological data interpola- tion – efforts not necessarily related to predictive modeling. “Spatial modeling” includes exercises of reclassification and overlay to further enhance data interpretations within GIS. However, spatial model- ing may also be employed as a bridge between GIS and predictive modeling outputs. Additionally, predic- tive water resource models (e.g., nonpoint source pol- lution, ground water, surface water) are emphasized, as opposed to logical and/or empirical models. While accounts of modeling software and GIS interfacing exercises continue to accumulate, limited effort has been spent on developing a unified structure or framework for interfacing GIS and predictive model- ing routines (Maidment, 2000). Rather, interfacing efforts have focused on individual models or select “groups” of models sharing common data structures.

The primary motivation behind the interfacing of models with GIS is the development of a tool to simultaneously analyze spatial and temporal variation of an event against fixed geographic entities employing a single means of display. Interpretation of simulation results is significantly improved through spatial visualization of model output (Engel *et al.*, 1997), but, of greater importance, results are enhanced by the employment of advanced spatial analysis techniques (point pattern, error, or multivariate analysis) of model results (Campbell *et al.*, 1989).

GIS has enjoyed a long history of use within the water resources field partially due to the early avail- ability of remotely sensed data suited for this purpose (Sample *et al.*, 2001) and has found applications in ground water hydrology (Hinaman, 1993; Raterman *et al.*, 2001); nonpoint source pollution tracking (Liao and Tim, 1997; Wong *et al.*, 1997); surface runoff mod- eling (Shamsi, 1996; Zollweg *et al.*, 1996); and general hydrology applications (Frankenberger *et al.*, 1999; Olivera and Maidment, 1999).

Early research efforts used GIS in parallel tracks of development by either employing GIS to estimate model input parameters or interfacing simulation models with GIS. Examples of model input estimation include work by Moore *et al.* (1988), in which a GIS was used to provide topographic attributes for model- ing hydrology and water quality within a watershed. Olivieri *et al.* (1991) used GIS software to develop input data for the Agricultural Nonpoint Source (AGNPS) pollution model (Young *et al.*, 1989). Parallel interfacing efforts include projects by Hession and Shanholtz (1988), in which a GIS was interfaced with AGNPS to evaluate strategies in efforts to reduce nonpoint source pollution to the Chesapeake Bay. Tim*et al.* (1992) employed GIS and interfaced two simpli- fied pollutant transport models to estimate phospho- rous loading and soil erosion from the Nomini Creek watershed in Virginia.

Additional GIS interface tools include Geographic Resource Analysis Support System (USACE, 1993), a raster GIS system, and TOPographic PArameteriZa- tion (TOPAZ), a group of software modules that links to a GIS to process raster DEMs to identify and quan- tify topographic features, including watershed divides (Garbrecht and Martz, 1997). Because it is a public domain GIS, GRASS source code is openly available, making it attractive for software developers (Ogden*et al.*, 2001). GRASS was linked to a number of water resource models including Area Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) (Srinivasan and Engel, 1991), AGNPS (Engel *et al.*, 1993; Park *et al.*, 1995), Soil and Water Assessment Tool (SWAT) (Srinivasan and Arnold, 1994), Soil Moisture-based Runoff MODel (SMoRMOD) (Zollweg *et al.*, 1996), Soil Moisture Runoff (SMR) (Frankenberger *et al.*, 1999), and Water Erosion Prediction Project (WEPP) (Savabi *et al.*, 1995). Additional accounts of interfacing models with GIS include efforts by Shea (1993), Tim and Jolly(1994), Tim *et al.* (1996), Lasserre *et al.* (1999), and Olivera and Maidment (1999).

ArcGIS, including ArcInfo and ArcView (Environ- mental Systems Research Institute, ESRI, Redlands, California), includes a number of interface modules useful to water resource modelers, including ArcInfo/ArcView GRID, a cell-based or raster-based geospatial data processing system (ESRI, 2000). GRID includes tools WATERSHED to delineate watershed boundaries; FLOWDIRECTION that iden- tifies flow directions; FLOW ACCUMULATION to quantify the area that drains into each cell; and SLOPE to calculate slope of each cell. ArcGIS Hydro, developed by the GIS in Water Resources Consortium, represents a geospatial and temporal data model developed exclusively for surface water resource mod- eling to operate within ArcGIS (Maidment, 2000). ArcGIS Hydro provides links between modeling tools and geospatial data, ArcGIS Hydro geodatabase, and time series data. For example, ArcGIS Hydro USA geodatabase contains river, stream, and water body networks, plus accompanying streamflow records (Maidment, 2000).

Review work covering interfacing GIS with various hydrologic process models and issues of scale and error propagation is examined in DeVantier and Feld- man (1993); Tsihrintzis *et al.* (1996) outline a variety of applications of GIS to water resource engineering including surface water, water supply and sewer sys- tems, nonpoint source pollution, and ground water modeling; and Ogden *et al.* (2001) focus on interfacing GIS with distributed hydrologic models.

## GUI AND WATER RESOURCE MODELING

A landmark development in information technology over the past decade, apart from massive improve- ments in hardware technology, has been the develop- ment of GUI. Motivations behind the development of GUI are many and varied. In general, well designed GUI may free the user from learning complex com- mand languages in which the user interacts with the computer by supplying lines of text commands. When utilizing this approach, the computer typically responds with text output to the display or to a file. An example within the water resource modeling envi- ronment is the early development of numerical mod- els using the formula translation (FORTRAN) computer language. These models were text-driven and navigated using a series of commands in a command line interface (CLI). For experienced users, a CLI may be a faster and more efficient approach to navigating the modeling environment, but it requires a stronger knowledge of the system architecture. A CLI contrasts with a GUI, where, within a GUI, most or all available commands for a process are simultaneously displayed and users are more readily capable of selecting the required operation. In addition to their visual component, GUIs make it easier to move data from one application to another.

It is reasonable to consider that a water resource model in current use is unlikely to be termed “state- of-the-art” or develop a wide following without employing GUI. This is illustrated in the current offering of water resource models widely available to the public. For example, the Enhanced Stream Water Quality Model (QUAL2E), the preferred model of the U.S. Environmental Protection Agency (USEPA) for total maximum daily load (TMDL) calculations, was enhanced to include GUI during its transition from a DOS-based program to a Windows-based application (USEPA, 1985). CE-QUAL-W2, a two-dimensional dynamic water quality model developed by the U.S. Army Corps of Engineers (USACE) Waterways Exper- iment Station (WES), included a preprocessor GUI for the release of Version 3.1 of the CE-QUAL-W2 soft- ware (Cole and Wells, 2002). The preprocessor GUI serves to ease the initial setup and execution of the FORTRAN modeling routine as well as attracting potential users who may have been previously cau- tious about utilizing a predominantly text-based mod- eling system. Additional, proprietary pre-processor and post-processor packages for CE-QUAL-W2 (e.g., Loginetics’ W2i and AGPM-2D pre-processors and post-processors, respectively) provide additional ease of data entry and visualization of model results, including animation. Other efforts include linking CE-QUAL-W2 with GIS for improved data entry and model result visualization (Ha *et al.*, 2003).

An exception to this apparent trend is the Hydro- logical Simulation Program – FORTRAN (HSPF) used by the USEPA (Bicknell *et al.*, 2001). HSPF can simu- late hydrologic and hydraulic continuous, steady state or dynamic behavior and water quality processes and can model well a large variety of streams and rivers. Applications include water quality planning, flood mapping, and evaluation of water erosion and sedimentation problems (Bicknell *et al.*, 2001). This model remains available as a GUI absent stand alone program but more recently has been incorporated into the USEPA GUI driven decision support system Bet- ter Assessment Science Integrating Point and Non- point Sources (BASINS) (USEPA, 2001) and similar systems (e.g., U.S. Department of Defense Watershed Modeling System, WMS, discussed in the next section of this paper).

### *Enhanced Graphical Display Capabilities Through Model Interface With GIS*

In conjunction with GUI development for water resource models, developers have focused on improv- ing the graphical display capabilities of model output. The renovation of the surface water runoff model HEC-1 and water surface profile model HEC-2, devel- oped by the USACE Hydrologic Engineering Center (HEC), into the Hydrologic Engineering Center – Hydrologic Modeling System (HMS) (HEC, 2001) and River Analysis System model (HEC-RAS) (HEC, 1997), respectively, concentrated on three elements: enhancement and expansion of model capabilities, introduction of GUI to navigate the model, and the expansion of capabilities to include an ArcView (ArcInfo) GIS interface (Brunner, 2002). This capabili- ty, designated HEC-GeoHMS (HEC, 2000) and HEC- GeoRAS (HEC, 1999), respectively, is a set of procedures, tools, and utilities for processing geospa- tial data in ArcView GIS (or ArcInfo) using GUI. The interface allows the preparation of geographic data for import into HEC-HMS and HEC-RAS and process- es simulation results exported from each of these models. As elucidated by Brunner (2002), water sur- face profile data and velocity data exported from HEC-RAS simulations may be processed by HEC-Geo- RAS for GIS analysis for floodplain mapping, flood damage computations, ecosystem restoration, and flood warning response and preparedness.

The Storm Water Management Model for the Per- sonal Computer (PCSWMM) (Computational Hydraulics Int., Guelph, Canada), MIKE SWMM (Danish Hydraulic Institute, Hørsholm, Denmark), and XP-SWMM (XP Software, Portland, Oregon), the graphically enhanced versions of the USEPA Storm Water Management Model (SWMM), have also been expanded to include stand alone GIS packages. This software can interface directly with the underlying database(s) of virtually any GIS/CAD system and allows ESRI MapInfo and AutoCAD layers/themes to be displayed. Data are extracted directly from an external GIS database – such as dBASE, Access, Lotus, Paradox, FoxPro, Btrieve, Excel, delimited text file, and more are supported, including open database computing driver (ODBC) compliant databases – using structured query language (SQL) queries and setup in PCSWMM GIS' internal database for “data tweaking” into a suitable model (i.e., element aggre- gation) (James *et al.*, 2002).

The focus of development and inclusion of GIS into the SWMM modeling environment is twofold. One focus provides a stand alone GIS system for drawing model elements (entities) and assigning their attributes. In this case, the modeler is capable of developing a schematic view or a real world view, complete with background maps and/or digital terrain photographs. This schematic may be enhanced by importing existing data from available sources. Another focus is to provide an intermediate step between GIS, project management software, and SWMM. In this case, PCSWMM, MIKE SWMM, and XP-SWMM GIS modules are configured to extract model data from the underlying GIS database(s) for incorporation into the model’s computational routines.

### *State-of-the-Art Decision Support Systems*

Current state-of-the-art DSS and modeling suites have focused on interfacing multiple models and GIS using GUI within a standalone package. These efforts are best illustrated by the development of Texas Water Resources Institute’s SWAT, USEPA BASINS, Systeme Hydrologique European (SHE), Modular Modeling System – Precipitation Runoff Modeling System (MMS/PRMS), U.S. Federal Emergency Man- agement Agency (USFEMA Hazards U.S. – Multihaz- ard (HAZUS-MH), and the Department of Defense series of Watershed, Ground water, and Surface water Modeling Systems – WMS, GMS, and SMS, respec- tively.

SWAT uses a GRASS GIS interface (Srinivasan and Arnold, 1994; Ogden *et al.*, 2001). The input interface in SWAT provides automatic subdivision of a watershed into grids or subbasins, which allows for extracting model input data from map layers and associated relational databases for each subbasin. The resulting output maps after model runs can be displayed through the output interface, which allows the user to select a subbasin from a GIS map. The three main components of a GIS interface in SWAT include: (1) pre-processor that generates subbasin topographic parameters and model input parameters;
(2) editing component for input data, and simulation execution; and (3) post-processor for viewing graphi- cal and tabular results. BASINS (USEPA, 2001) is an interface developed by the USEPA in ArcView to enable state regulatory agencies to quickly analyze water quality problems. BASINS 2.0 and later ver- sions use an

ArcView implementation of the SWAT model. This allows the user to assess watershed load- ings and receiving water impacts at various levels of complexity. ArcView geographic data preparation, selection routines, and visual output streamline the use of the models, while a Web-based interface in BASINS 3.1 allows increased ease of access to geo- graphic and water resource data, including automatic data updates. MIKE BASINS, a proprietary version of BASINS, uses an enhanced postprocessor for output

o ArcView, Excel, Access, and AVI movies for anima-tion (Jha and Das Gupta, 2003).

SHE is a hydrologic watershed model resultingfrom an international collaboration in Europe to develop a comprehensive model capable of linkingsurface and subsurface water movements (Abbott *et al.*, 1986a,b). MIKE SHE (Borah and Bera, 2003,2004), a proprietary version, provides significant enhancements to the original SHE, including soluteand sediment transport, geochemistry, biodegrada-tion, and three-dimensional visualization. MIKE SHE and MIKE 11, a stormwater hydrology and hydraulicsmodel, were effectively coupled to evaluate hydrology, hydraulics, and water quality of a wet grassland(Thompson *et al.*, 2004). Similar to SHE, MMS/PRMS, developed by the U.S. Geological Survey(USGS), is a modular-based, integrated watershedand water quality model with established interfacesto both ArcInfo GIS and GRASS GIS (Leavesley *et al.*, 1996a,b). MMS/PRMS allows selective linking ofspecific modeling processes to construct the appropri- ate model (Ogden *et al.*, 2001).

HAZUS-MH (USFEMA, 2005) employs an ESRI ArcGIS 9 interface to integrate models to estimate potential losses from hurricane winds, floods, and earthquakes within the United States. Using a database of building locations, infrastructure, and populations, HAZUS-MH uses GIS to spatially dis- play hazards, economic loss, and populations at risk from natural events. Three levels of damage and eco- nomic loss estimates are available, ranging from “rough” estimates derived from nationwide databases in a Level 1 Analysis to use of more refined data in a Level 2 Analysis, with Level 3 Analysis providing experts in the field the opportunity to modify loss parameters based on specific local conditions. The HAZUS-MH Flood Loss Model provides maps and reports related to flood events through use of a hazardanalysis module to determine flood elevation and velocity and a loss module to estimate economic and physical damage.

The Watershed Modeling System (WMS) (EMRL, 2004a) is a comprehensive graphical modeling envi-ronment for analysis of watershed hydrology and hydraulics. The system includes a GIS module with direct linkage capability to ESRI ArcGIS 9 and allows such functions as automated basin delineation, cross-section extraction, and GIS overlay computations. The software system supports the hydrologic models HEC-1 (HEC-HMS), TR-20, TR-55, Rational Method, National Flood Frequency (NFF), Modified Rational Method (MODRAT), and HSPF and the hydraulic models HEC-RAS and CE-QUAL-W2. The software’s modular design enables the user to select modules in custom combinations, allowing the user to choose only the required hydrologic models. GMS (EMRL, 2004b) and SMS (EMRL, 2004c) share similar architectures, in which models are dynamically linked and may be added or removed from a simulation in a modular fashion. Outputs from simulation runs may be dis- played graphically using a variety of plotting tech- niques.

### *Interfacing Approaches*

Approaches, techniques, pros and cons of modeland GIS interfacing attempts are well elucidated within the literature. Numerous prior works (Fedra,1993; Nyerges, 1993; Livingstone and Raper, 1994; Tim and Jolly, 1994; Goodchild *et al.*, 1996; Singh andFiorentino, 1996; Liao and Tim, 1997; Hartkamp *et al.*, 1999; Gurnell and Montgomery, 2000; Maidment,2000; Maidment and Djokic, 2000; Vieux, 2001;Shamsi, 2002) extensively outline the continuum ofmodel GIS interface tools, ranging from loose cou-pling/linking to tight coupling/combining or full inte-gration of the interface within the GIS model system.The interfacing of models to GIS is not a novel con-cept and has been tried and tested by numerous orga-nizations over a significant period (Nyerges, 1993).However, the lack of consistent data protocols andseeming lack of interest by commercial softwaredevelopers in creating universal data transfer stan-dards (Vckovski *et al.*, 1999) has stifled the develop-ment of standardized frameworks for terminology,data exchange formats, and interface proceduresbetween predictive water resource models and GIS.Terminology to describe interfacing efforts includessuch words as “couple,” “link,” “combine,” "interface,""modeling within," and "integrate."

Linking GIS and models typically uses data generated from within GIS as inputs to the model, and output is transferred to GIS for display and spatial analysis. Simple linkage strategies exchange data between software systems using ASCII format or common binary files (Fedra, 1996). Advanced linkage configurations may employ multiple overlays, interpolation routines, and user defined triggers within GIS to enhance spatial analysis of the model output. Linking approaches have been widely adopted by researchers and developers due to their relative ease of development but are limited by the reliance of GIS and the model on specific data formats. Most GIS data structures (e.g., vector, raster) allow data trans-fer in both the ASCII and binary file formats, while many water quality models have fixed file formats for organizing input data (Liao and Tim, 1997). Additionally, this approach rarely allows the user to take full advantage of the functional capabilities of GIS (e.g., spatial analysis tools), as GIS is principally used as a display tool. A linkage approach prevents users from exploiting the full potential of either GIS or the predictive model as illustrated by Yang *et al.* (1999) and Marsili-Libelli *et al.* (2001). Both studies employed Mathematics Library (MATLAB) (The Mathworks, Inc., 1999) to act as a data bridge between the water quality model output and GIS. GIS was utilized onlyto spatially display the results of the simulation, and interpretive tools were rendered inactive, effectively suppressing further spatial or temporal analysis of model results.

Combining differs from linking, where information is passed between the model and GIS via memory-resident data models (using client-server programs available in most GIS software) rather than external files (Liao and Tim, 1997). Data are exchanged automatically, and the display of model results may be configured with the interactive tools of GIS (Burrough, 1997). This approach improves computational performance and interactivity between the two software systems, translating into a more sophisticated modeling environment. Works by Vieux *et al.* (1998) and Whittemore and Beebe (2000) outline the somewhat subtle differences between "linking" and "combining" models with GIS. Model and GIS interactivity remains limited in these cases; however, data transfer (input and output) between the software systems is automated and remains hidden from the user. Vieux *et al.* (1998) notes the additional, if limited, analysis tools available within the "combined" system. Techniques of overlay, buffer, and location siting are avail-able for use and increase the interpretation capabilityand value of employing GIS. Whittemore and Beebe (2000) examine the USEPA watershed modeling system BASINS, which combines the instream water quality model QUAL2E with the watershed loading and transport models HSPF and SWAT. The system utilizes ArcView GIS as a display and interpretation interface, but each model remains separate and acts as a plug in module rather than being embedded within GIS.

The most sophisticated approach to interfacing GIS and predictive models is termed "integration" or "embedding." This approach is founded on incorporating the functional components of one system within the other, eliminating the need for intermediate transfer software (Liao and Tim, 1997). Through the use of relational databases and expert systems, GIS and the integrated model (or vice versa) are no longer maintained as independent units. Rather, a seamless integration is developed by sharing as many processes and data sources as possible to reduce redundancy within the system. Development of an embedded system may require the employment of a common data organization and transfer system so data format conversions or manipulations remain concealed to thefront end user. Considerable communication between GIS programmers and modelers is necessary to accomplish the required software programming. However, the end product breeds enhanced performance and increased flexibility during scenario analysis as the array of GIS spatial analysis tools remains available to the user. Due to the complexities involved in developing these systems, limited attempts at integrating predictive water resource models with GIS are recorded. More commonly, integrated systems utilize simplified models (Tim, 1996; Liao and Tim, 1997). The significant effort required to develop a water quality model is examined in Tsanis and Boyle (2001), whereas a two-dimensional water quality model to simulate currents and pollutant transport in lakes and coastal areas is developed using the AVENUE programming language within ArcView GIS. The use of this GIS-based interface module facilitates improved communication of the basic patterns and relationships associated with hydrodynamic/pollutant transport simulation but also illustrates the inherit limitations and simplifications required to develop a water quality model within GIS. Simulation constraints include steady state flow and the lack of contaminant exchange between sediments and/or the use of decay coefficients. However, by "integrating" the hydrodynamic simulation module to GIS, basic GIS functionality is expanded and enhanced while retaining interpretative capabilities.

Limitations of interfacing strategies are commonly triggered due to incompatibility of data structures, software requirements, and model-GIS functionality requirements (Tim, 1996; Burrough, 1997; Liao and Tim, 1997). By limiting GIS to functioning as a dis- play medium, a "linked" approach underutilizes the inherent functional capabilities of GIS, as interactivi- ties between adjacent locations within a model are ignored. Combining and integration approaches pro- vide more sophistication and achieve software inter- activity more readily but are stymied by the significant development cost and effort required for an advanced interfacing project. Prior to initiating an interfacing project, a focus on efficiency, maintenance costs, and ease of use for the end user should be eval-uated (Fedra, 1993; Nyerges, 1993). The development of an integrated system requires significant effort and is likely the reason most interfacing efforts have evolved through linking models with GIS (Hartkamp *et al.*, 1999). A modular approach to GIS and model interfacing allows for increased flexibility and lucidity during technology transfer exercises. Modular devel- opment of water quality routines and transport schemes at varying levels of scale, each with a common data transfer capability, serve to greatly expand DSS capability and act as pathfinders to a more structured model development environment.

The elimination of intermediary software to process, interpret, or modify model output prior to GIS trans- fer significantly reduces computational time and error. The choice of interface strategy will ultimately be guided by pertinent research objective(s), expertise of the developers, and availability of resources.

*Interface Strategy Considerations*

Limitations to the rapid and efficient coupling of GIS and hydrologic models lie in the existing differ- ences between data models and methods of variable handling. The GIS data model is an efficient spatial relationship database capable of uniformly processing vast quantities of data specific to individual layers of information over a large spatial region (Maidment, 1993). Within hydrologic modeling, focus is typically localized rather than regional, and the desire is to col-lect extensive information over a small area. In addi- tion, the exclusion of a time dimension within the GIS data structure deters from the interactivity of a GIS predictive model system. This absence interferes witha user's ability to readily model, within GIS, spatial variability over time. The relational database struc- ture of GIS also limits the collusion of GIS and some predictive models.

Within a GIS database, the relationship concept is drawn from the classic relational database model rep- resentation of a relation being an association between two sets of data using a key item common to both (Maidment, 1993). Thus a user is capable of process- ing and joining vast sets of information based on asso- ciated spatial features. However, as noted by Maidment (1993), a database relation is a weak con- nection between two entities. When compared to the mathematical rigor of a hydrologic model, spatial relationships do not effectively capture the governing hydrologic algorithms. Differential equations utilized in a typical hydrology model thus have limited oper- ability within a GIS data structure. Accordingly, hydraulic models utilizing advanced algorithms or complex mathematical structures are currently inca- pable of being fully integrated into a GIS relational database. This is emphasized when noting the attempts listed in Table 1 at integrating models with GIS. The typical result is a simplified or limited func- tionality model being applied within GIS, marginaliz- ing the usability of the final product. This is underscored in Fistikoglu and Harmancioglu (2002) and Xu *et al.* (2001), where, in attempts to develop a more refined predictive system, the level of model sophistication diminished in response to the demands of modeling within the GIS environment.

The choice of modeling software utilized in theinterface exercise often determines the degree to which models and GIS may be interfaced. Complexmodels are more apt to be "linked" to GIS, whereas a simple or simplified version of a model often has a greater probability of being successfully "integrated" within GIS. De Paz and Ramos (2002) were resignedto linking the Ground water Loading Effects of Agri- cultural Management Systems (GLEAMS) model(Leonard *et al.*, 1987) and ESRI PC-Arc/CAD GIS dueto the complexities inherit within the model. GLEAMS is a one-dimensional, deterministic, and physically based model that simulates percolation, runoff, nitrogen, and pesticide leaching, as wellas erosion and sedimentation on a daily time step(de Paz and Ramos, 2002). Of the four submodels(hydrology, erosion/sedimentation, transport, and nutrient fate), only the hydrology and nitrogen nutri- ent models were utilized. GUIs were developed to facilitate the simulation process and allow nonspecial- ist GIS users to simulate different crop-managingalternatives and to display the results as thematic maps (de Paz and Ramos, 2002). Efforts by Yang *et al.* (1999) required the use of both “modeling within” and “linked” approaches to achieve their goals. Within this project an integrated approach was established in ERDAS Imagine (Leica Geosystems, 1999) (an image processing and GIS software package) to generateimages of chlorophyll distribution, Secchi depth, and phosphorous as derived from Satellite pour l'Observa- tion de la Terre (SPOT) imagery. The predictive model QUAL2E was linked to the GIS system using a MAT-LAB bridge due to the complexity of water quality simulation that could not be executed within a GISenvironment (Yang *et al.*, 1999). Tsanis and Boyle (2001) developed a closely coupled two-dimensional,hydrodynamic/pollutant transport GIS model operat-ing within ArcView GIS.

Using the ESRI GIS programming language AVENUE as a bridge, the close coupling of the hydrodynamic simulation model to the GIS expanded and enhanced the basic functionality of GIS. AVENUE provided a well defined mechanism for allowing user written routines to be called from within the normal user interface of the GIS package and provided criti- cal functionality to access data structures such as points, lines, grids, graphic elements, and the related database records used in model input and output transactions (Tsanis and Boyle, 2001). ESRI has since transitioned from its proprietary scripting language AVENUE and now focuses efforts on developing Visu- al BASIC (VB) code to be used within ESRI software. There are no translators between the two languages, and this unexpected move by ESRI has likely slowed the development of new interface projects as modelers

TABLE 1. Selected Model and GIS Interface Efforts.

| Model | System | Focus | Interface Level | Data Format | References |
|---|---|---|---|---|---|
| GLEAMS | ArcInfo | Hydrology, ground water | 1 | V | Stallings *et al.* (1992) |
| CMLS | ArcInfo | Hydrology | 1 | V | Zhang *et al.* (1990) |
| MODFLOW | ArcInfo | Ground water flow | 1 | R | Hinaman (1993) |
| ANSWERS | GRASS | Watershed erosion and deposition | 1 | R | Srinivasan and Engel (1991) |
| SPUR | ERDAS | Watershed hydrology | 1 | R | Sasowsky and Gardner (1991) |
| AGNPS | ArcInfo | Hydrology | 1 | R | SathyaKumar and Farell-Poe (1995) |
| QUAL2E | ERDAS | Water quality | 1 | R | Yang *et al.* (1999) |
| MATLAB (Mathematics Programming) | ArcView | Surface water quality | 1 | V | Masrili-Libelli *et al.* (2001) |
| MIKE 11 | ArcView | Stormwater hydrology and hydraulics | 1 | V, R | Thompson *et al.* (2004) |
| MIKE SHE | ArcView | Watershed hydrology, water quality | 1 | V, R | Borah and Bera (2004) |
| HEC-1 | ArcInfo | Flood modeling | 1 | R | Chang *et al.* (2000) |
| SWMM | ArcView | Stormwater hydrology and hydraulics | 1 | R | Huber and Dickinson (1988) |
| MIKE BASINS | ArcView | Watershed hydrology, water quality | 2 | V, R | Jha and Das Gupta (2003) |
| AGNPS | ArcInfo | Water quality | 2 | V | Tim and Jolly (1994) |
| AGNPS | GRASS | Watershed erosion | 2 | R | Engel *et al.* (1993) |
| AGNPS | ERDAS | Hydrology | 2 | R | Olivieri *et al.* (1991) |
| AGNPS | GRASS | Hydrology | 2 | R | Park *et al.* (1995) |
| SWAT | GRASS | Watershed hydrology, water quality | 2 | R | Srinivasan and Arnold (1994) |
| SMoRMOD | GRASS | Rainfall-runoff | 2 | R | Zollweg *et al.* (1996) |
| HSPF, QUAL2E | ArcView | USEPA BASINS modeling system | 2 | R, V | Whittemore and Beebe (2000) |
| Runoff Model | ArcView | Urban runoff | 2 | R | Wong *et al.* (1997) |
| HAZUS-MH | ArcInfo | Natural Hazard Damage Assessment | 2 | R | USFEMA (2005) |
| SMR | GRASS | Hydrology | 2 | R | Frankenberger *et al.* (1999) |
| WEPP | GRASS | Watershed hydrology | 2 | R | Savibi *et al.* (1995) |
| PSRM | ArcInfo | Watershed runoff management | 2 | R,V | Shamsi (1996) |
| WHPA | ArcInfo | Ground water | 2 | V | Vieux *et al.* (1998) |
| AgriFlux | IDRISI | Ground water | 2 | V | Lasserre *et al.* (1999) |

| | | | | | |
|---|---|---|---|---|---|
| MODLFOW | ArcView | Ground water | 2 | V | Tsou and Whittemore (2001) |
| MATLAB (Mathematics Programming) | ArcView | Ground water | 2 | V | Raterman *et al.* (2001) |
| GLEAMS | Arc/CAD | Ground water NPS pollution | 2 | V | de Paz and Ramos (2002) |
| SCS runoff Model | MapInfo | Pesticide runoff | 3 | R | Li *et al.* (2002) |
| AGNPS | ArcInfo | NPS pollution control | 3 | R | Liao and Tim (1997) |
| IDOR2D | ArcView | Water quality and pollutant transport | 3 | R, V | Tsanis and Boyle (2001) |
| USLE | IDRISI | Soil erosion | 3 | R | Fistikoglu and Harmancioglu (2002) |
| PDTank | ArcView | Watershed management | 3 | V | Xu *et al.* (2001) |
| ‘Screening’ Models | ArcView | Ground water | 3 | V | Tim *et al.* (1996) |

Interface Level: 1 = linked, loose coupling, ad-hoc; 2 = combined, tightly coupled, particle integration; 3 = integrated, embedded coupling, modeling within.
Data Format: R = raster; V = vector.

and developers wait for standardization from indus- try. Efforts by Lasserre *et al.* (1999) and Fistikoglou*et al.* (2002) are examples of model integrations with-in GIS. Lasserre *et al.* (1999) used the Pascal comput- ing language to develop a simple advection transport model within IDRISI GIS (Clark University, 1999), coupled to the Agricultural Flux (AgriFlux) unsatu- rated zone transport model (Banton and Larocque, 1997). Although validated for the test case using the Modular Transport in 3-Dimensions (MT3D) model (Zheng, 1990) and appearing to be satisfactory for assessing nonpoint nitrate contamination in ground water, the approach is simplified in that it excludes preferential flow, bypass flow, hydrodynamic disper- sion, and adsorption desorption reactions (Lasserre *et al.*, 1999). As noted by Lasserre *et al.* (1999), theinfluences of these processes cannot be neglected and may constitute a limitation to the practical use of the modeling system. Fistikoglou *et al.* (2002) integrated the empirical universal soil loss equation (USLE) into IRDISI GIS to identify rainfall-based erosion and transport of nonpoint source pollution. Limitations in GIS and simplistic empirical model integration are exposed within this work, including the loss of accura- cy experienced by employing a “simple” versus “sophisticated” model and difficulties encountered during the marriage of the predictive model to GIS.

### *GIS and Predictive Model Interfacing Challenges*

The significant number of efforts in which models and GIS have been interfaced (Table 1) suggests that, while interfacing is not necessarily a trivial exercise, it remains a tractable software engineering problem (Hartkamp *et al.*, 1999). However, additional chal- lenges of developing interfaced systems that satisfy output data requirements and support error analysis methods for data quality control exist.

Spatial data error is generated from measurement, digitization, or interpolation error, and since models are simplified realizations of reality, additional erroris anticipated in model output. Within GIS, two pri- mary classes of uncertainty are present, positional error (from errors in digitizing or geocoding) and the- matic error (incorrect grouping or attribute data). Since the cumulative effect(s) of these errors on inter- faced systems is poorly understood, error analysis and model output verification become increasingly impor- tant as additional models are interfaced with GIS. By having greater focus on reliability and model output quality, error analysis may be used to optimize sam- pling density and delineate required model complexi- ty. Noted by Hartkamp *et al.* (1999), conventional error propagation theory can be used to assess the quality of modeling results only if they are influenced by random errors. Random errors affecting input data for GIS or the predictive model may include errors of measurement, observation, or data entry. Within the model, error may stem from the quality of input data, the fitness of the model, and the methods by which the data and model interact. In attempts to minimize the error generated from several GIS procedures, Bur- rough (1986) developed a series of propagation rules. Alternate efforts at quantifying GIS error include probability modeling, which remains problematic due to the variety of spatial data processing procedures and the rigorous requirements of probabilistic data gathering. Techniques of statistically quantifying error propagation, including Monte Carlo simulations and analytical approaches, are thoroughly examined in Burrough and McDonnell (1998) and Heuvelink(1998).

An additional concern raised during GIS and model interfacing exercises is the inclusion of time as an additional dimension within GIS. GIS analyses mayaccount for time in two ways. One approach is to visualize a time series of historic survey or remote sensing data as a series of overlays that may be analyzed using statistical procedures (Croft and Kessler, 1996). This analysis approach effectively documents past trends but has poor predictive power, especially for scenario evaluations. The second technique avoids this shortcoming by using predictive models to repre- sent future time variation. Model results are typically viewed as a predictive time series within GIS as a series of overlays (Wilson *et al.*, 2000).

### *GIS Interfaces and Data Sources*

Burgeoning modelers may not fully comprehend the design limitations of GIS specific data structures and assumptions, including those relating to capture, storage, analysis, and interpretation of data, which may unknowingly lead to inaccuracies and misunder- standing (Burrough and Frank, 1995). Vector struc- tures are most suited to representation of networks, connected objects, and features defined by discrete boundaries, while raster structures are most effective- ly employed to represent continuous entities in space. Examples of misuse of these data structures include: using polygons with finite boundaries to represent the distribution of soil properties (or any continuously varying entity); and conversely, digitization of soil group polygons from vector coverage to a raster cover- age (rasterization), hence distorting the original boundaries of the vector-based format. Most common- ly, the decision to employ vector or raster data for a particular attribute is dictated by the available data structure, with raster data enjoying prevalence because of its simplicity of use and broader availabili- ty (Garbrecht *et al.,* 2001). Additionally, elevation data for model use is dependent upon the resolution from which it is derived. For this reason, focus is placed on research efforts using raster format.

Over the past two decades, the USGS (2004) has digitized almost the entire United States into grids of elevation values or digital elevation models (DEMs) at resolutions up to 30 meters. DEMs are a popular raster format that is used to display and extract topo- graphic information such as drainage patterns, slope, and aspects that are needed for hydrological model- ing. DEMs have had a profound impact on water pplications of GIS by stimulating the research and development of distributed hydrologic and nonpoint source pollution models and their linkage to GIS (Wilson *et al.*, 2000). With the use of DEMs, there are questions with respect to the source, accuracy, storage requirements, and applicability of spatial data, GIS, and models. Several research efforts have used DEMs for developing GIS hydrological integration and addressing several of the aforementioned issues (Wolock and Price, 1994; Zhang and Montgomery, 1994; Garbrecht and Starks, 1995; Cluis *et al.*, 1996; Garbrecht and Martz, 1999; Fortin *et al.*, 2001; Flem- ing and Neary, 2004).

Researchers are now facing additional challenges when using very high resolution data sources. Signifi- cant efforts continue to be made to address ways to improve the integration of very high resolution eleva-tion data into hydrological models. Two very high res- olution data of particular interest to modelers are derived from light detection and ranging (LIDAR) and NEXRAD remote sensing systems. LIDAR systems, also known as “airborne laser-scanning systems,” are installed on low flying aircraft that travel along a well defined flight plan to produce submeter topographic maps. These systems are capable of measuring the canopy top and the underlying ground surface (Haar- brink, 2003). LIDAR has become a fixture of present- day mapping missions, providing cost effective means to achieve high accuracy results in hydrological mod- eling as well as other applications (Adkins, 2002). With LIDAR data, modelers can now extract more accurate and detailed DEM data.

NEXRAD system consists of approximately 166 Doppler radar stations that provide spatial rainfall estimates at approximately 4 km resolution, with nominal coverage of 96 percent of the conterminous of the United States (Crum *et al.,* 1998; Hardegree *et al.*, 2003). Significant progress has been made in using NEXRAD data toward distributed parameter hydrologic modeling for storm runoff, flood, and long- term river forecasting (Georgakakos *et al.,* 1996; Smith *et al.*, 1996; Vieux and Farajalla, 1996; Bedient *et al.*, 2000; Vivoni and Sheehan, 2000). Despite these advances, NEXRAD data records contain significant gaps in which no data are available, and additional research should be conducted to compare radar and gauge estimates in watershed locations with multiple, overlapping radar coverage (Hardegree *et al.*, 2003).

Even though raster datasets appear to dominate the hydrological modeling landscape, the choice of data format should consider storage and processing capabilities and the scale of the study area. Therefore, vector-based format can be a viable option depending on the requirements. The vector data options primari-ly include digital line graph (DLG) and triangulated irregular network (TIN) (Garbrecht *et al.*, 2001).

DLGs are contour-based structures consisting of digitized contour lines with a specific elevation. TINs have a continuous surface of connected triangles with known elevations at the vertices of each triangle. Several research efforts are making significant advances in using vector data in water resource mod- els (Kopp, 1998; Hellweger and Maidment, 1999; Dob- bins and Abkowitz, 2002; Vivoni *et al.*, 2004; E.B. Daniel, J.P. Dobbins, E.J. LeBoeuf, P.H. Martin, and M.D. Abkowitz, unpublished manuscript).

Differing GIS subroutines may exploit differences between techniques when performing similar opera- tions. Unfortunately for modelers, vendor supplied documentation regarding such techniques is often lacking (Miles and Ho, 1999). Thus, different GIS sys- tems may require adopting altered intermediate data exchanges when using the same predictive model. This undesirable GIS specificity is capable of produc- ing contrasting results when employing the same model across a range of GIS systems (Heuvelink, 1998). Prior to interfacing, modelers must identify potential impacts behind manipulating models for GIS that were not intentionally developed for interac- tivity with spatial analysis software.

## FUTURE DIRECTIONS FOR GISINTERFACING SYSTEMS

Wide spectrums of application exist for future phases of GIS and predictive model interfacing. Research and development in further developing mod- ular interfaces for sets of popular resource models is a valuable future endeavor. This modular approach allows for wide application of GIS display capabilities over numerous hydraulic regimes. Similarly, further expansion of customized GIS modules for predictive modeling, capable of incorporating time series data displays of model outputs, would greatly assist deci- sion makers and response planners.

The increasing availability of worldwide digital data for model input will ultimately allow hydrolo- gists and modelers to rapidly customize and calibrate a model for specific catchments. The data manage- ment capability of GIS is attractive in organizing and maintaining these forms of data for model use. How- ever, additional efforts are required to further stan- dardize the data formats to ensure broad usability of information between predictive models and GIS with- out having to employ advanced conversion intermediates (Vckovski *et al.*, 1999). A standardized data format or uniform conversion software will serve to accelerate analyses while reducing accountable con- version error and reducing time spent filtering or sorting data. However, the increased availability of spatial data burdens the interface requirements between GIS and predictive models. Additional data links between the GIS database and the model will require development in order to maximize the use of catchment specific data. ArcGIS Hydro represents an example GIS augmented to specifically cater to sur- face water resource modeling efforts (Maidment, 2000). This development will serve to decrease the number of gross abstractions and generalizations for climate, streamflow, soil type, and vegetation data currently employed during model applications.

Advancements and the increasing availability of inexpensive computing power provide opportunitiesfor broadening the spectrum of model applicationsbeing interfaced with GIS. The development and interfacing of two-dimensional and three-dimensionalmodels with GIS have been made possible byadvances in computing technology. With respect to interface strategy efficiency, advancements in comput- er processor speeds serve to reduce the time required to evaluate a scenario. While the “linkage” approachis the least sophisticated of the interfacing strategy trio, it remains the easiest to employ. As such, “link-age” approaches remain viable when interfacing avariety of models to GIS within applications wherecomputational delay is acceptable. Dobbins andAbkowitz (2002) illustrate the effectiveness of a link- age structure in the development of an inland marine risk management information system. The system was designed to support real-time response to bargeaccidents or terrorism activities and is based on the interfacing of GIS, databse management systems, global positioning systems, and the Internet. In the event of an incident, the system allows en routeresponders to view incident details via an Internet GIS map service and, alternatively, may be employedto evaluate risk resource allocation and potential response strategies. Additional efforts by Martin *et al.* (2004) and E.B. Daniel, J.P. Dobbins, E.J. LeBoeuf, P.H. Martin, and M.D. Abkowitz (unpublished manuscript) underscore the value of modular develop- ment of these DSS. Modular development introduces a level of flexibility commonly absent from a fully integrated GIS model system and provides a platform for model customizations for a target region. The introduction of remote Internet capability, as illus- trated by Dobbins and Abkowitz (2002), is another seeming trend in further expanding the capabilities of GIS model environments and DSS. The ability to per- form on-site modeling of a spill incident through a secure Internet connection is a significant aid to the execution of timely response and abatement activities.

## DISCUSSION AND CONCLUSIONS

Analysis of Table 1 indicates that numerous efforts at interfacing GIS and predictive models have been undertaken within multiple disciplines and a variety of outcomes achieved. Watershed scale and basin scale predictive models have subjugated to a great number of interfacing attempts. Linking and combin- ing approaches greatly outnumber accounts of com- plete model GIS integration. These findings underscore the inherit difficulties in harnessing the full mathematical and time predictive power of interfacing modeling systems with GIS. Difficulties do not stem from lack of effort or user experience but from fundamental differences between the predictive model and GIS data structures (Table 2). GIS has experi- enced much publicity within the scientific community as a valuable new technology. It is important that users and developers retain the process of perception and resist the temptation to allow GIS to drive the methods by which models are applied. As noted, most predictive models were not developed to directly inter- face with GIS. However, this should not keep GIS from taking a significant role during data visualiza- tion and interpretation exercises. The relative incom-patibilities between advanced predictive model databases and GIS databases should not discredit the role GIS may play in engineering analyses.

Efforts by Hartkamp *et al.* (1999) at developing standardized terminology for GIS and model interfac- ing is a notable step in developing a standard for future work. However, the seeming trend toward “out of the box” utilization and interfacing of GIS with pre- dictive models without having a thorough knowledge of either is discouraging. The ability of users to rapid- ly develop interfaces between GIS and models without recognizing critical error sources undermines the goals of melding these technologies. Inquiries into the scientific value of developing complex systems to assist a user’s problem-solving capacity have been raised in much of the literature (e.g., Goodchild, 1993; Burrough, 1997; Whittemore and Beebe, 2000). A lack of established conventions for interfacing GIS and simulation models has limited the development of protocols and guidelines for such efforts. Burrough (1997) noted that merely achieving an interface between GIS and a model does not guarantee an improved understanding or increase the predictive power of the interfaced software system. However, while development of a common software code to bridge GIS and predictive models would certainly increase the number of interfacing efforts, this stan- dardized approach would serve to ease efforts during calibration and error analysis by forcing the develop- ment of baseline protocols. These protocols require flexibility to accommodate the desired range of models to be interfaced, but provide tractability of results. The

TABLE 2. Comparison of Interface Techniques.

| Interface | Characteristics | Pros | Cons |
|---|---|---|---|
| Linking | • Manual data exchange between model and GIS | • Simplest interface to develop<br>• Discrete file transfer allows for modular interchange of model outputs | • Limited GIS functionality<br>• System dependence on GIS or model output format<br>• Incompatibility of operating systems and model environments<br>• Typically requires multiple user interfaces |
| Combining | • Automatic data exchange between model and GIS | • Flexible interface allows modular exchange of models<br>• Retains GIS functionality<br>• Improved computational performance and interactivity | • Requires more complex program-ming than linkage strategies<br>• May require multiple user inter-faces |
| Integrating | • Insertion of GIS into a modeling environment or model into a GIS | • Data transfer is transparent to user<br>• Single user interface<br>• Retains GIS functionality | • Requires simplification of GIS or model for full integration<br>• Complex programming and data management requirements |

subsequent reduction in the volume of code manipulation or transformation during an interfacing exercise serves to further minimize the amount of expected error within the system.

Visual display, spatial analysis, and data manage- ment capabilities of GIS make it an attractive technology for application within predictive modeling. The vast increase in nationwide data availability and advances in computing speed provide bases for use of more advanced, data intensive models during interfacing exercises. Strategies for future development of GIS and predictive model coupling may include: (1) development of a GIS module specific for modeling applications that includes multidimensional and time series display capabilities, such as ArcGIS Hydro, which makes several advances in this regard (Maid- ment, 2000); (2) continued development of modular generic interfaces compatible with defined series of water resource models; and (3) development of advanced water resource model code for GIS inser- tion.

Within increasing information availability, researchers and developers must work in unison to generate improved data management and interpreta- tion tools (e.g., the GIS in Water Resources Consor- tium). Predictive models coupled with the display capabilities of GIS enhance the decision-making pro- cess and have wide applicability across many engi- neering disciplines. Delays in response or unanticipated economic problems arising in environ- mental management are symptomatic of a lack of knowledge or insight into the complexities of aquatic

systems. The development of easily executable data- intensive DSS serve to ensure adequate management of valuable water resources. Development of user- friendly interfaces and efficient algorithms will serve to eliminate the need for decision makers to have extensive backgrounds in water resource modeling or GIS data structures to efficiently use developed sys- tems when solving problems of water pollution, assist- ing water resources agencies in establishing and monitoring regulations, and prioritizing environmen- tal remediation activity.

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