# GIS as an information technology framework for water modeling

Durmus Cesur

## ABSTRACT

The sustainable and equitable management of water requires integrated analysis which includes the integration of a multitude of modeling systems at the core. The linkage of the modeling systems and components is the main bottleneck to achieve the integrated modeling solutions that maintain the integrity of the entire environmental system for comprehensive analysis, planning and management. In this paper, the use of a Geographic Information System (GIS), as an integration framework for the water modeling systems, together with object-oriented data modeling and programming schemes is explained. Integration of the modeling systems on a GIS platform, through a surface-water-specific GIS data model, Arc Hydro, and interface data models as data repositories for common water features, hydrologic and hydraulic modeling elements, is presented with a case study. Arc Hydro served as an integration data model for the simulation models of concern. Time series data transfer between modeling system at the information exchange points is facilitated using object-oriented linkage programs, and relationships among the modeling elements are established through Arc Hydro.

In the case study, the HEC-HMS hydrologic model and the HEC-RAS hydraulic model are integrated into an automated floodplain mapping application on a GIS. The implementation of the integration methodology is presented.

**Key words** | Arc Hydro, geographic information system, HEC-HMS, HEC-RAS, interface data model, model integration

**Durmus Cesur**
San Antonio River Authority,
100 East Guenther St., San Antonio, TX 78204,
USA
Tel.:+1 210 302 4248
Fax: +1 210 227 4323
E-mail: *dcesur@sara-tx.org*

## INTRODUCTION

Water management necessitate a holistic approach, through the integration of the multitude of modeling systems comprised of many components and subcomponents due to the interrelationship and interactions in the natural or artificial water networks (Charnock *et al.* 1996; Djokic *et al.* 1996; Price 2000; Moore *et al.* 2004; Gijsbers & Gregersen 2005). The simulation of water-related phenomena such as flooding, erosion, environmental contamination, water supply and treatment requires integration of the modeling systems with differences. The differences include (NOA 2001; CUAHSI 2002; Cesur *et al.* 2004; Moore *et al.* 2004; Gijsbers & Gregersen 2005):

(a) domains and environments
(b) concepts
(c) dimensionalities
(d) temporal and spatial scales
(e) units, projections and categorizations
(f) platforms
(g) data from various data sources
(h) modeling components.

A flexible integration scheme with a common interface and linkage overcoming these differences among different modeling systems is needed to describe the complex processes comprehensively, to allow the process interactions so that better decisions related to floodplain management, erosion control, environmental remediation, optimized water supply and treatment, and others could be made (NOA 2001; CUAHSI 2002; Blind & Gregersen 2005).

doi: 10.2166/hydro.2007.008

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

For example, a flood management system in general requires a meteorological model to forecast the rainfall, a hydrologic model to convert rainfall to runoff, a hydraulic model to route the flow through the stream network and to predict the timing and severity of the flooding, a decision support model based on statistical, or some other technique, to convert the results to meaningful warning levels and associated actions, and a socio-economic assessment model to evaluate the flood damage and loss, to plan and carry out recovery efforts efficiently, and to take necessary measures for the future (NOA 2001; Koussis *et al.* 2003; CIS 2003; Adebe & Price 2005). Building a single monolithic model encompassing all the processes water goes through may not be a feasible option, and direct integration of different models may require manipulation of the source code of the models, as well as reconciliation between time series structures and feature representations of the water modeling systems (Charnock *et al.* 1996; Moore *et al.* 2004; Whitaker 2004). Therefore, there is a need to increase the flexibility of modeling systems as well as to devise flexible, adaptable methodologies to implement integrated modeling systems from available building blocks of the existing models and systems (Blind & Gregersen 2005).

A GIS can provide a viable framework for the simulation modeling integration since the modeling systems include space, together with time, as a common denominator. A GIS is a natural choice for Earth modeling system studies and practices since it captures the common geospatial elements among the modeling systems. A range of GIS applications have been developed, covering a variety of water issues including water quality, floodplain mapping, water supply and distribution, wastewater, and water-related decision support systems and others. GIS has been used as a support system for hydrologic model data storage, operation, manipulation, preparation (pre-processing), data visualization and analysis (post-processing), and become an integral tool for water management decisions and practices (Clark 1998; Correira *et al.* 1999; Choi *et al.* 2005; Vivoni & Richards 2005). GIS and models have been integrated to have powerful tools using the strength of both systems, and to incorporate them in spatial decision support systems (SDSS) to facilitate time- and cost-efficient water resources planning and management solutions (Xu *et al.* 2001; Gad & Tsanis 2003).

In this paper, integrated modeling system development based on GIS through the use of object-oriented data modeling programming schemes has been described. A methodology for model integration on a GIS platform and its implementation at a pilot scale using Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) as a hydrologic model and river analysis system (HEC-RAS) as a hydraulic model is presented.

## BACKGROUND

A GIS integrated with enterprise database management systems could manage large volumes of geospatial data to provide spatially distributed parameters for modeling (Gao *et al.* 1993; Vieux 2001). However, use of GIS for modeling data management and integration is generally hampered by the differences in scale, precision, data structure, data meaning, representation of the reality, and others, between a GIS and a simulation model (Charnock *et al.* 1996; Vieux 2001; Whitaker 2004).

The GIS and simulation model integration (i.e. coupling) ranges from loose integration to tight integration levels (Charnock *et al.* 1996; Clark 1998). The loose integration links GIS and models through communicating programs or bridges (i.e. generally script tools with associated dynamic link libraries (DLLs) for linkage), in which the model and GIS programs are executed separately and simply share data through the bridge (Charnock *et al.* 1996). The tight integration combines GIS and models with the two components communicating directly with each other through the common data structure and the database (Clark 1998).

The current technology trend in the integration of the systems is to use GIS as one of several applications that support a central database of information (Clark 1998). A GIS is viewed as a part of the database support, analysis, and decision support system (Clark 1998). The loosely coupled applications using data bridges are best to use for this setup, since they facilitate interaction of the applications through the central database or with each other, and allow modification without altering other system components (NOA 2001; Whitaker 2004). The loose coupling increases the portability of the system and its components

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

(NOA 2001). The loosely coupled applications could be facilitated by using data models that provide robust data structures (Kopp 1996). A data model defines a standard data structure, and provides solid data meaning for a GIS application and models (CUAHSI 2002; Whitaker 2004). Therefore, appropriate data models for data organization, query, retrieval and exchange could assist in modeling data management and integration in a GIS environment (Roberts & Moore 1998). In this regard, the Arc Hydro data model could be used for the model integration since it provides a GIS data structure for surface-water-specific core elements and time series included in hydrologic and hydraulic modeling (Maidment 2002). The flexible object-oriented programs could be developed to link various modeling components or models interchangeably in diverse combinations that are appropriate for the water phenomenon of interest in a time- and cost-efficient manner (Blind & Gregersen 2005). The integrated modeling systems can be built upon object-oriented technologies to have reusable, adaptive, portable tools, with consistent federated databases, linked with short-term, long-term monitoring systems, and driven by user-friendly interface (Batelaan *et al.* 1996; Price 2000; Blind & Gregersen 2005). They could be incorporated with information, knowledge management systems on distributed computing environments which are expected to be the future integration platform for modeling, GIS and other systems if the challenges posed could be resolved effectively regarding the interoperability, communication infrastructure and architecture, security, performance, composability, operational management, transactions, reliable messaging and others (Abel *et al.* 1998; Bishr 1998; Clark 1998; Wolter 2001; Louis 2002; CUAHSI 2002; Anderson & Moreno-Sanches 2003; Choi *et al.* 2005).

The methodology presented in this paper utilizes GIS-based object-oriented data models and data links formed with the relationships and object-oriented utility programs to transfer temporal data between a GIS and the simulation models. In the case study, HEC-HMS and HEC-RAS simulation models are integrated by the transfer of information at the discrete points along a stream network through scripts calling DLLs. For the integration, a separate data model has been developed and a separate linkage program has been written for each model.

## THE FRAMEWORK FOR GIS-BASED MODEL INTEGRATION

The framework for the model integration on GIS is formed by the interface data models, object-oriented linkage programs and relationships established between common geospatial features and modeling elements. Additionally, a ModelBuilder platform served as a common graphical interface to interact with the integrated modeling system, and to combine data model elements and various utility programs. The integrated modeling system elements are described in the following subsections.

### The modeling systems

The HEC-HMS modeling system was developed by the US Army Corps of Engineers (USACE). The system is used for precipitation runoff simulation for both rural and urban watersheds. It includes most of the computational capabilities included in HEC-1 along with some new capabilities (USACE 2000). It also provides a user-friendly graphical interface. Additionally, it offers a quasi-distributed basin runoff method (Mod-Clark) (USACE 2000).

The HEC-RAS modeling system was developed by the USACE. It is primarily used for calculating water surface profiles for one-dimensional, steady, gradually varied flow in natural or artificial channels (USACE 2002). It uses a standard step method to calculate the water surface elevation based on the conservation of energy.

### Interface data models

An Interface Data Model was generated to define a GIS data structure for the model data storage required by a particular simulation model (Whitaker 2004). The data model stores the data that the simulation model requires prior to execution, as well as outputs from the simulation model to facilitate two-way (i.e. bi-directional) communication between GIS and a simulation model (Whitaker 2004). The two-way communication between GIS and the models is critical specifically for the linkage of the models that require data from each other for simulation such as hydrologic and hydraulic models, surface water models and

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

groundwater models, sediment models and river models (Blind & Gregersen 2005).

The communication between the Interface Data Model and the simulation model is efficient and manageable since the Interface Data Model is designed to work specifically with the simulation model (Whitaker 2004). Furthermore, by storing model data in the geodatabase, and through the use of common hydrologic features in different simulation models as extensions of core Arc Hydro features, data can be shared among multiple simulation models (Whitaker 2004). A single source of hydrologic geospatial data, such as watershed and stream network information, can be used in multiple simulation models by using Arc Hydro as a common integration data model. The output from one simulation model, such as HEC-HMS, may be used as input into another model, such as HEC-RAS, by bringing the data into an Interface Data Model for HMS, through Arc Hydro, and then through an interface data model for HEC-RAS (Whitaker 2004).

Interface Data Models provide a means of storing geospatial data for model input, model output and sharing data through Arc Hydro, while still maintaining the autonomy of simulation models. The interface data models also provide a mechanism for querying and retrieving modeling data (CRWR 2003). Through the use of these models additional visualization and spatial processing capabilities for the modeling data using GIS could be readily achieved. They support GIS-based model configurations to reflect what-if scenarios, new basin and floodplain developments, and allow for storage, setup and update of new modeling scenarios (Robayo *et al.* 2004). They also facilitate storage of the modeling time series data in a manner that will be compatible with the standard GIS-based time series storage scheme and associated tools (CRWR 2003). They assist in the incorporation of modeling systems to the enterprise spatial database, information, decision support and knowledge management systems. In the case study, the interface data models are generated for the HEC-HMS based on version 2.2.2, and for the HEC-RAS based on version 3.1.1.

### Model information exchange

The integrated modeling through geospatial integration consists mainly of a central GIS database and the simulation models required for the analysis. Each simulation model is executed independent of other components in the system (Robayo *et al.* 2004). The model outputs are imported into the GIS to be used as inputs to another model or for further geospatial analysis, interpretation and visualization. The data transfer between simulation models takes place at information exchange points within the GIS (CRWR 2003; Robayo *et al.* 2004). The information exchange point is defined as a point of interest which holds significance for the flow of water for integrated water resources modeling (Robayo *et al.* 2004). These points are typically located at HydroJunctions for surface water, which may be linked to watersheds, cross sections and other features through established relationships. The types of information that may be exchanged at information exchange points include time series and other information (CRWR 2003).

In the case study, the information exchange occurs between model simulations, rather than during a given simulation (CRWR 2003). This approach is not as powerful as fully coupled, simultaneous execution of simulation models. However, it is easier to implement and provides useful and flexible solutions. The developed loose coupling scheme makes it possible to substitute different models to simulate a given hydrologic or hydraulic process, provided that an interface data model, linkage relationship and associated program have been generated to communicate with a GIS (Whitaker 2004).

## THE MODELBUILDER AS A GRAPHICAL INTEGRATION PLATFORM ON GIS

The GIS-based integrated modeling scheme was implemented using a GIS workflow model. ArcGIS 9 provides a geoprocessing framework through a ModelBuilder environment that allows geoprocessing tasks to be linked together in GIS workflow models to perform a major component of the business process. The ModelBuilder environment could be used to link the standard tools in ArcGIS 9, to custom tools that are generated by the user from code, scripts or GIS models.

ArcGIS executes the script to perform work when it is called from a workflow model. Once a workflow model has

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

been generated, it may be reused and inserted into other models. The case study presented in this paper uses both standard ArcGIS tools and custom script tools in a workflow model. The scripts could call a dynamic link library (DLL) or executable. HEC-HMS and HEC-RAS are two executables used in this research. In the case study, a number of DLLs were generated to link GIS and the simulation models.

## THE CASE STUDY: AUTOMATED FLOODPLAIN MAPPING

The goal of the floodplain mapping application developed was to convert from NEXRAD rainfall data to flood inundation polygons for Rosillo Creek, a tributary of the Salado Creek, a part of San Antonio River in Texas (Figure 1). The Rosillo Creek basin covers an area of 75 square kilometers, and has a short response time to rainfall events, on the order of hours. The automated procedure for the case study included converting the rainfall time series to runoff hydrographs at the outlet for each watershed in the Rosillo Creek basin using HEC-HMS. Then, the hydrographs are used as inputs to a HEC-RAS hydraulic model to obtain cross section water surface elevations, and GIS processing is performed to produce a flood map using the modeling outputs and terrain data.

The HMS Interface Data Model contains watersheds and SchemaNodes with an HMSCode attribute. This attribute links features in the geodatabase to their representation in an HMS Basin file (Figure 2). The RAS Interface Data Model extends the Arc Hydro CrossSection feature class to include Stream_ID, Reach_ID and Station attributes. These attributes locate a given cross section in a RAS model (Figure 2). The RAS Interface Data Model also includes a boundary feature class which is taken from an ArcGIS extension called HEC-GeoRAS, defining the boundary of analysis for the floodplain.

Both HEC-HMS and HEC-RAS use the HEC's Data Storage System (DSS) for storing time series information;

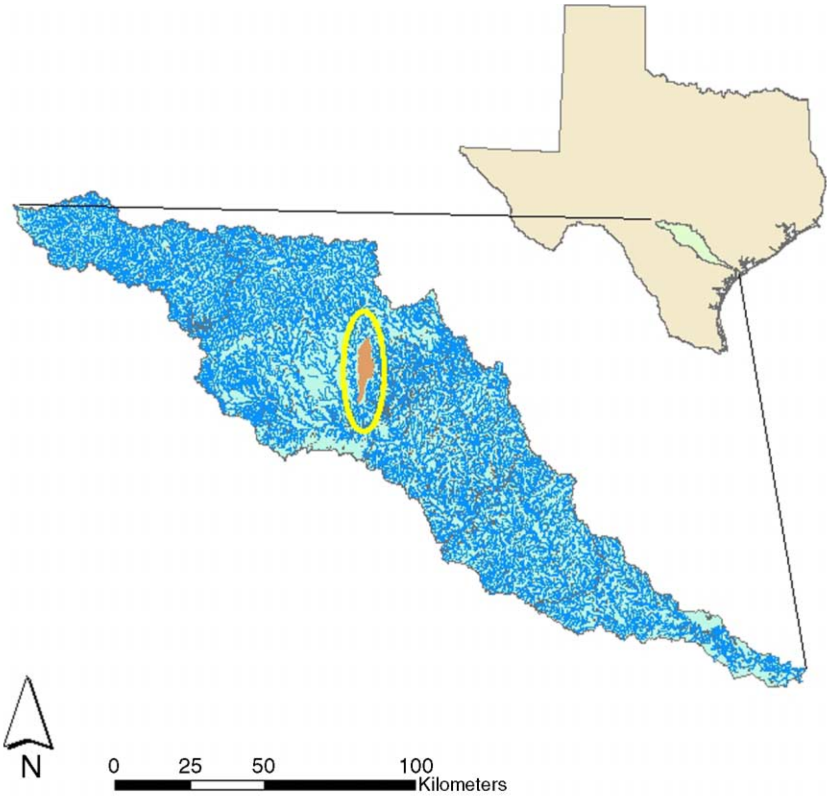

**Figure 1** | Rosillo Creek tributary of Salado Creek, San Antonio River Basin in Texas.

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

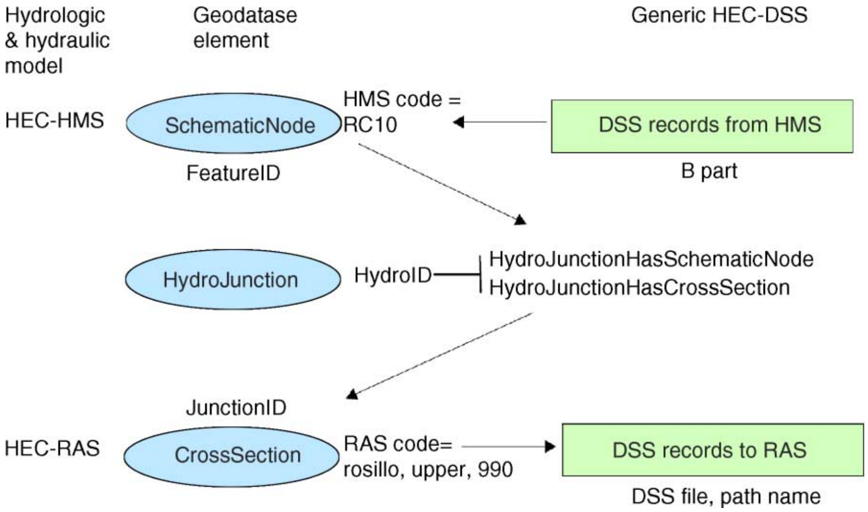

**Figure 2** | Model and GIS linkage.

therefore the Interface Data Models for HMS and RAS share a common DSSTSValues table and DSSTSType table (USACE 1995). These tables extend the Arc Hydro Time-Series and TSType tables to support parameters required by DSS. Both the HEC-HMS and HEC-RAS Interface Data Models are incorporated into a single geodatabase for Rosillo Creek. Both Arc Hydro features (such as Hydro-Junctions) and the DSS time series tables are used to transfer information between Interface Data Models for each simulation model. Data were populated in the geodatabase and the simulation files required by HMS and RAS before the simulation.

## Watershed and hydrometeorological data

GIS data were used in modeling included the stream network, cross sections, watersheds and 0.61 m (2 ft) contours. The contours were used to generate a digital elevation model (DEM) for the area. The Arc Hydro schema was applied after the data were loaded into a geodatabase. The resulting geodatabase was further modified to incorporate the HMS and RAS Interface Data Models. Information exchange points were established between the GIS and HMS at the outlets of 17 watersheds within the basin. The outlets that were located on the stream network were stored in the HydroJunction feature class. The information exchange points between the GIS and RAS were established at each next downstream CrossSection from the HydroJunction, serving as an outlet of each watershed. The configuration of 223 cross sections in the creek was considered dense enough to associate hydrographs of Watershed with the next downstream CrossSection without compromising the integrity of the data (Whitaker 2003). When importing RAS results back into the geodatabase, all Cross-Sections were used. HMS and RAS project files (and other supporting files) were also set up for the creek. These files contain the information necessary to run an HEC-HMS or HEC-RAS simulation. Certain sections of those files reflect inputs from the GIS, such as rainfall data for an HMS meteorological record. Features in the HEC-HMS and the HEC-RAS files possess identifiers to link them with features in the geodatabase. A historic storm event recorded by NEXRAD radar on 1 July 2002 from 4:00 AM to midnight has been used to provide rainfall input for the rainfall–runoff hydrologic and hydraulic transformations (Robayo *et al.* 2004).

## The model integration application

The application was implemented as the ModelBuilder work-flow model in ArcGIS 9, called as “Map2Map” (Figure 3). The application served as a prototype to prove versatile model integration on GIS platform. The workflow model contains 19 tools, including script tools, model tools and standard ArcGIS tools. The scripts call both DLLs and executables to perform processes that are not readily available through standard ArcGIS tools. Map2Map integrates HEC-HMS and HEC-RAS into a flood mapping application, by establishing the

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

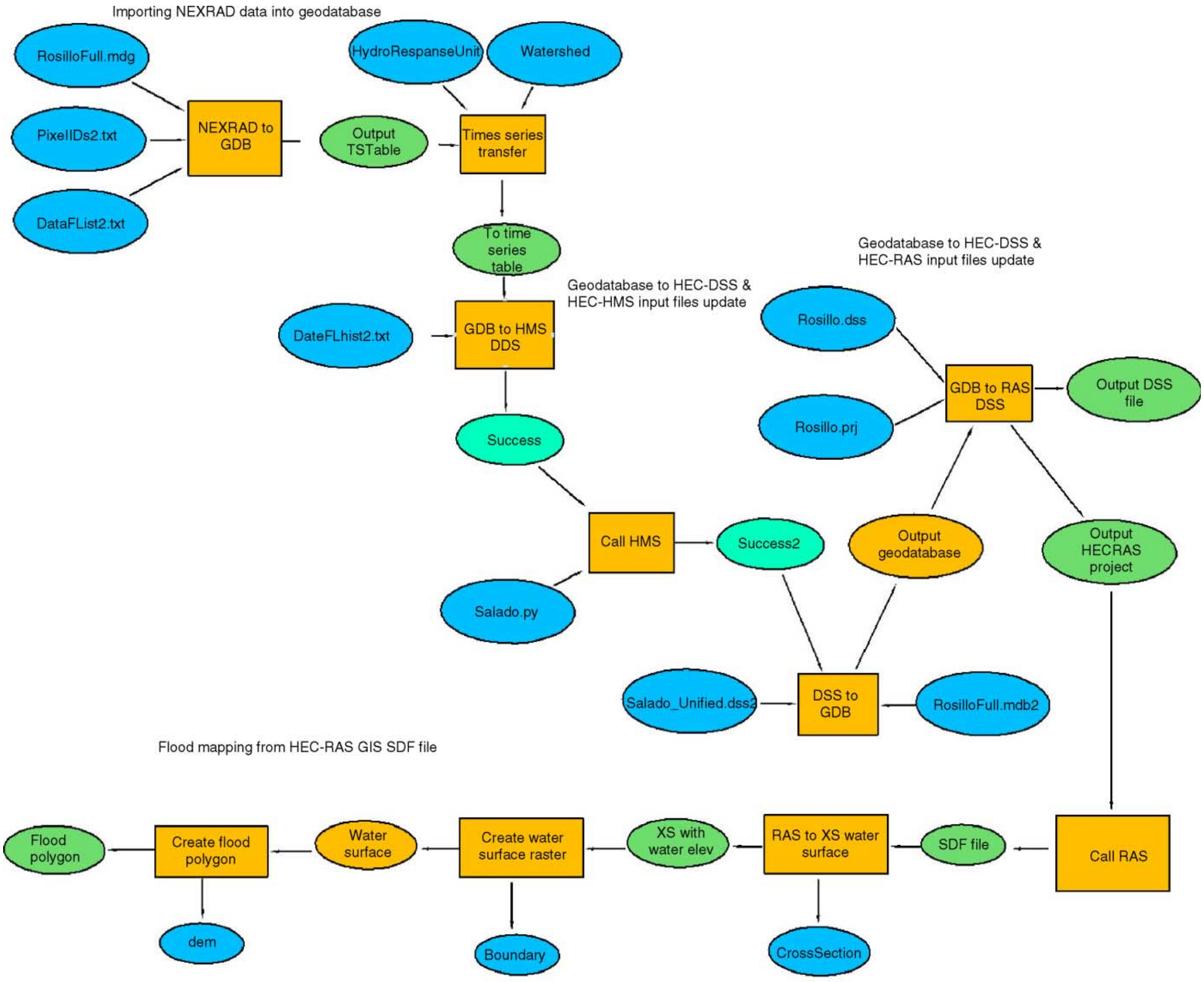

**Figure 3** | The Map2Map application (adapted from Robayo *et al.* 2004).

connectivity through the information exchange points. The basic sequence of model execution includes the steps described in the following paragraphs.

The NEXRAD rainfall data are stored in individual ASCII data files, which are indexed by a DataFileList file. A PixelID text file is used to identify NEXRAD cells for which time series data are available. In the workflow model the ASCII NEXRAD to GIS bridge matches available cells with NEXRAD polygon features in the geodatabase, and then imports the time series of rainfall into the Arc Hydro TimeSeries table. Then, the model transfers time series associated with the NEXRAD polygons to watersheds for the basin using area weighted average of rainfall for a watershed at each time step based on the extent of coverage of the watershed with the NEXRAD polygon. Then, the data were passed to the HEC-HMS hydrologic simulation model to calculate an outflow hydrograph for each watershed. The GIS TimeSeries to HMS DSS bridge (i.e. DLL) based on HEC public domain access libraries for HEC-DSS is used to write a DSS file to supply HMS with rainfall data by using the linkage established between a watershed in the geodatabase and a corresponding basin object in the HMS basin file with the HMSCode attribute in each watershed (USACE 1987, 1991).

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

After a DSS file has been written, the HMS hydrologic simulation model was executed using a Visual Basic® shell function enhanced with delay capabilities incorporated into HMSCaller DLL. The model performs rainfall–runoff calculations to generate a set of runoff hydrographs for nodes representing watershed outlets and stream confluences in the stream network for each watershed in the basin (Robayo 2005). In the Map2Map workflow model, HMS runs its entire simulation without user interaction. The GIS waits for the completion of the HMS execution before continuing with the next step.

HMS writes the results of its simulation into a DSS file. The DSS to GIS TimeSeries DLL based on HEC public domain access libraries is used to transfer time series data from the DSS file into a geodatabase time series table. The linkage between DSS file and the geodatabase is established using a HMSCode attribute stored in the SchemaNode feature class. The SchemaNode feature class is related to HydroJunction at the appropriate location on the stream network. CrossSections describing the river channel are also related to HydroJunctions on the stream network. The next downstream CrossSection from a given SchemaNode was located through HydroJunction relationships, and each runoff hydrograph time series was matched to the closest cross section to the node at the information exchange points. The GIS TimeSeries to RAS DSS DLL makes the appropriate association to outflow hydrographs for each CrossSection to transfer time series data from the geodatabase to a RAS DSS file. The tool also updates the RAS project file to reflect the new time series records.

HEC-RAS is called by the RASCaller script to calculate the water surface elevation at each CrossSection, using the watershed hydrographs supplied in a DSS file from the geodatabase. The SDF file (i.e. HEC file containing the results of a RAS simulation) containing water surface profiles for each cross section along the creek is obtained.

After HEC-RAS has finished its simulation, the resulting cross section elevations were associated with CrossSection features in the GIS. In the application, first, the SDF file is converted to XML format using SDF RAS output to XML bridge, and then the water surface elevation data in the XML file is imported into the geodatabase to be stored as an attribute of the CrossSection feature class using XML to GIS Cross Section Elevations bridge.

The Map2Map generates a raster representing water surface elevations when water surface elevations have been attributed on CrossSections. The model uses the CrossSections as soft break lines with elevations taken from the water surface elevation attribute. The output triangular irregular network (TIN) is clipped with the convex hull of cross sections used in the HEC-RAS simulation to the analysis boundary (Whitaker *et al.* 2004). The resulting TIN is then converted to a water surface raster for further processing, and parts of the TIN interpreted outside the boundary is removed (Whitaker *et al.* 2004). The land surface elevation raster is subtracted from the water surface elevation raster to create a raster representing the depth of inundation. The grid cells of positive depth are converted to polygons and dissolved to generate a flood inundation polygon (i.e. flood map for a given storm).

## RESULTS AND DISCUSSIONS

The integrated modeling system is initially tested using the July 2002 storm event and Rosillo Creek watershed data. The integrated modeling outcomes have been checked with the outcomes of the individual model runs to ensure the proper implementation. The computational time of the integrated modeling run was 2 min on an Intel XEON CPU with 2.20 GHz and 1 GB RAM (Robayo *et al.* 2004), and integrated modeling outcomes were found to match the outcomes of individual model runs. In the continuation phase of the implementation, the GIS-based integrated modeling system has been tested using various other watershed and rainfall data (design and historical storms) and found to be accurate (Knebl *et al.* 2005; Robayo 2005).

The Map2Map model proved the viability of integration of modeling systems on the GIS platform for various water-related applications. The integration scheme is flexible and portable since the models and associated data can be substituted with different data and models, or applied to other basins for various water concerns of interest (CRWR 2003). The models, components of the models and associated geospatial and time series data can be changed. For example, the cross sections, watersheds can be changed by simply dragging and dropping different datasets onto the model diagram, and different time series of rainfall can be

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

substituted in the model by simply changing the data file list parameter in the NEXRAD to GDB bridge (CRWR 2003).

Interface data models based on object-oriented data modeling in GIS made it possible to incorporate the simulation modeling systems into enterprise spatial databases, decision support, information and knowledge management systems. The interface data models made it possible to store, query, retrieve and analyze modeling data in the GIS environment using spatial databases based on object-oriented data models. The interface data models provided further spatial analysis, visualization and quality control and quality assurance capabilities for the modeling. They also facilitated the evaluation of the model performance, determination of the system, input and output parameter updates and model modifications, and possible upgrades in the model conceptualization and the associated structure, by integrating them with the spatial decision support system (NOA 2001).

In the continuation phase, the integrated modeling system was incorporated into the prototype enterprise spatial information and workflow management system, called a "Regional Watershed Management System" (RWMS), using the more complete and refined versions of the interface data models, and versioning capabilities of the enterprise spatial database built using Microsoft SQL Server 2000® and ArcSDE 9.0®, and web portal using ArcIMS® (Burmeister *et al.* 2005).

In the implementation, data transfers, specifically the time series data, between modeling systems and GIS have been accomplished flexibly using object-oriented utility programs. These programs could easily be modified to accommodate the data transfers among different data structures and data formats using the features of object-oriented programming such as inheritance and polymorphism. These features can speed the development for the incorporation of additional simulation models into the integrated modeling system.

## CONCLUSIONS

In this paper, the simulation model integration on a GIS using Arc Hydro as a common integrator data model, and the interface data models, which are linked using object-oriented programming tools through geospatial information exchange points, are explained. The simulation models, data models and linkage tools are assembled together on a ModelBuilder interface. The methodology has been proven to be feasible through the implementation at a prototype scale. Arc Hydro and the interface data models provided the data structures for the communication of GIS and the modeling systems. Time series and other attribute data transferred between a GIS and modeling systems at information exchange points using object-oriented linkage programs.

The interface data models facilitated two-way communication between models and GIS by providing mapping between data and parameters of the model, and its corresponding GIS representation (CRWR 2003; Robayo *et al.* 2004). Additionally, the interface data models provided a mechanism for storing, querying and retrieving modeling data in a GIS environment integrated with spatial databases (CRWR 2003). Through the use of these models in GIS, additional visualization and spatial analysis capabilities for the modeling data were achieved (CRWR 2003). These capabilities assisted in the evaluation of models and their parameters, quality control and quality checks. Additionally, the interface data models facilitated storage of the modeling time series data in a manner that will be compatible with the standard GIS-based time series storage scheme and associated tools (CRWR 2003). The interface data models also enabled the incorporation of modeling systems into the enterprise spatial database, information, decision support and knowledge management systems.

The major disadvantages with the interface data models in GIS are found to be the increased storage requirements for model data. Additionally, the interface data models led to a slight loss in overall system performance due to spatially enabling the modeling data, geometric network and relationship classes in particular. Furthermore, numerous data transfer operations between GIS and modeling systems to facilitate the GIS and model integration contributed to this loss. However, the loss is negligible compared to the time required to set up, run the models individually and transfer the data between them. Additionally, the automated method is more systematic and less error-prone as compared to the manual processing (Robayo 2005). The interface data models can be further standardized and refined, the common model elements may be incorporated to the base model, further object-oriented features can be allocated in the data models and the linkage programs, and GIS-compatible input and

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

output formatting options for modeling systems could be developed to further streamline the integrated modeling process and to reduce the time due to expensive input and output operations between the GIS and the modeling systems (Cesur *et al.* 2004). The configuration and support tools for the integrated modeling system need to be developed and incorporated as well to provide a more complete, robust enterprise GIS environment for modeling, decision-making and workflow management, and to obtain an end-user product with further capabilities such as real-time modeling. There is a need to integrate the further quality control, quality check procedures to the system together with the development of additional procedures to automate and streamline the existing and possible future modeling workflows.

The integration scheme implemented is flexible and may operate with any simulation model, so long as that model receives or passes the right kind of time series data at the right information exchange points. For example, in the application developed, a hydraulic simulation model other than HEC-RAS could have been used to produce water surface elevations on cross sections, provided that the model has a cross section data or something similar that is common between the model and the corresponding integration GIS data model. In the case study the integration data model was Arc Hydro, but this could as well be replaced with some other base data model, or even may be dropped as long as the relationships between modeling systems could be established through some mechanism such as cross-reference tables between modeling elements that are used for the information exchange. For all the possible improvements, however, the model needs to accept flows at key cross sections and return elevation data associated with all cross sections to fit with the integration mechanism proposed. The nature of the information exchange points and the information being passed through them guides the development of the integrated modeling system.

Further improvement in the integrated modeling would be a development of a robust scheme for trapping, handling errors and evaluation of the uncertainties. Additionally, incorporation of scenario management to the integrated modeling system to test a variety of different model configurations or scenarios to determine the optimum solutions is needed as well. A more robust and refined technique for exchanging information other than through the GIS at information exchange points may need to be developed to generalize the integration for water management applications other than the floodplain mapping such as water quality, water supply, wastewater and water treatment. As a further step, information exchange between the modeling systems without carrying out the entire simulation can be developed together with the interpolation and extrapolation capabilities. A future improvement in the integrated modeling system could include the ability to produce multiple floodplain polygons for unsteady flow to depict the temporal change in the flooded area. The geographically integrated modeling system development could further be enhanced by incorporating modules for enhanced system iterations, sensitivity analysis and optimization. When fully developed, the integrated modeling system with associated support systems and tools could assist in the evaluation of flood mitigation and control alternatives, flood alert, flood forecasting and other water and watershed management activities.

## ACKNOWLEDGEMENTS

The views and information presented in this paper are of the author, and not those of other individuals or organizations. The author would like to thank San Antonio River Authority, City of San Antonio, and Bexar County. The author would like to acknowledge the University of Texas Center for Research in Water Resources, especially Dr. David R. Maidment and his team, and Texas A&M University, especially Dr. Francisco Olivera, PBS&J, ESRI, and the US Army Corps of Engineers Hydrologic Engineering Center.

## REFERENCES

Abel, D. J., Ooi, B. C., Tan, K. & Tan, S. H. 1998 Towards integrated geographical information processing. *Int. J. Geog. Inf. Sci.* **12** (4), 353–371.

Adebe, A. J. & Price, R. K. 2005 Decision support system for urban flood management. *J. Hydroinf.* **7** (1), 3–15.

Anderson, G. & Moreno-Sanches, R. 2003 Building web based spatial information solutions around open specifications and open source software. *Trans. GIS* **7** (4), 447–466.

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

Batelann, O., Wang, Z.-M. & De Smedt, F. 1996 An adaptive GIS toolbox for hydrological modelling. In *Application of Geographic information systems in Hydrology and Water Resources Management* (ed. K. Kovar & H. P. Nachtnebel), IAHS, Wallingford, UK, pp. 3–10.

Bishr, Y. 1998 Overcoming the semantic and other barriers to GIS interoperability. *Int. J. Geog. Inf. Sci.* **12** (4), 299–314.

Blind, M. & Gregersen, J. B. 2005 Towards an Open Modelling Interface (OpenMI): the HarmonIT Project. *Adv. Geosci.* **4**, 69–74. Available at: http://www.copernicus.org/EGU/adgeo/4/adgeo-4-69.pdf, last visited in November, 2005.

Burmeister, W. S., Zardo, P. & McArthur, K. E. 2005 Enterprise GIS to manage water resources simulation models. In *Proceedings of ESRI International User Conference, San Diego, CA*. Available at http://gis.esri.com/library/userconf/proc05/papers/pap2341.pdf, last visited in December, 2005.

Cesur, D., Beene, E. C., Englehart, K. N. & Graham, S. T. 2004 Integrated GIS-based modeling system development for water resources. In *Proceedings of the American Water Resources Association, Specialty Conference on GIS and Water Resources III, 17–19 May, Nashville, TN*. CDROM, AWRA, Middleburg, VA.

Charnock, W. T., Hedges, P. D. & Elgy, J. 1996 Linking multiple process level models with GIS. In *Application of Geographic Information Systems in Hydrology and Water Resources Management. Proceedings of the HydroGIS '96 Conference, Vienna, Austria, 16–19 April* (ed. K. Kovar & H. P. Nachtnebel). Krips Repro, Meppel, The Netherlands, pp. 29–36.

Choi, J.-Y., Engel, B. A. & Farnsworth, R. 2005 Web-based GIS and spatial decision support system for watershed management. *J. Hydroinf.* **7** (3), 165–174.

CIS 2003 *Common Strategy on the Implementation of the Water Framework Directive (CIS): Best Practices in River Basin Planning Work Package 2: Guidance on the Planning Process*. Available at: http://dqa.inag.pt/dqa2002/port/docs_apoio/doc_int/12/PlanningGuidance.pdf, last visited in October, 2005.

Clark, M. J. 1998 Putting water in its place: A perspective on GIS in hydrology and water management. *Hydrol. Process.* **12** (1998), 821–824.

Correia, F. N., Da Graça Saraiva, M., Da Silva, F. N. & Ramos, I. 1999 Floodplain management in urban developing areas. Part II: GIS-based flood analysis and urban growth modelling. *Wat. Res. Man.* **13** (1), 23–37.

CRWR 2003 *A Geographically Integrated Hydrologic Modeling System*. Center for Research in Water Resources, Report, University of Texas at Austin, TX.

CUAHSI 2002 *Consortium of Universities for the Advancement of Hydrologic Science Inc (CUAHSI) Hydrologic Information Systems. Technical Report* 2. Available at: http://www.cuahsi.org/publications/cuahsi_tech_rpt_2.pdf, Last visited in December, 2005.

Djokic, D., Coates, A. & Ball, J. E. 1996 Generic data exchange: integration models and data providers. In *Proceedings of 4th International Conference/Workshop Integrating Geographic Information Systems and Environmental Modeling, 21–25 January, Sweeney Convention Center, Santa Fe, NM*, pp. 639–645. CDROM. National Center for Geographic Information and Analysis (NCGIA), Santa Barbara, CA.

Gad, M. A. & Tsanis, I. K. 2003 GIS methodology for the analysis of weather radar precipitation data. *J. Hydroinf.* **5** (2), 113–126.

Gao, X., Sorooshian, S. & Goodrich, D. C. 1993 Linkage of a GIS to a distributed rainfall-runoff model. In *Environmental Modeling with GIS* (ed. M. F. Goodchild, B. O. Parks & L. T. Steyaert). Oxford University Press, Oxford, pp. 182–187.

Gijsbers, P. J. A. & Gregersen, J. B. 2005 *OpenMI Standard in a nutshell, v.1.0, HarmonIT Paper*. Available at: http://www.harmonit.org/docs/the_openmi_standard_in_a_nutshell_v1.pdf, last accessed in September, 2005.

Knebl, M. R., Yang, Z. L., Hutchison, K. & Maidment, D. 2002 Regional scale flood modeling using NEXRAD rainfall and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event. *J. Environ. Mngmnt.* **75** (2005), 325–336.

Kopp, S. M. 1996 Linking GIS and hydrological models: where we have been, where we are going. In *Application of Geographic Information Systems in Hydrology and Water Resources Management. Proceedings of the HydroGIS '96 Conference, Vienna, Austria, 16–19 April* (ed. K. Kovar & H. P. Nachtnebel). Krips Repro, Meppel, The Netherlands, pp. 133–140.

Koussis, A. D., Kagouvardos, K., Mazi, K., Kotroni, V., Sitzmann, D., Lang, J., Zaiss, H., Buzzi, A. & Malguzzi, P. 2003 Flood forecasts for urban basin with integrated hydro-meteorological model. *J. Hydrol. Engng.* **8** (2003), 1–11.

Louis, H. 2002 *Web Services are the Future of Geoprocessing*. Available at: http://www.geoplace.com/gw/2002/0206/0206opng.asp, last visited in September 2005.

Maidment, D. R. (ed.) 2002 *Arc Hydro: GIS For Water Resources*. ESRI Press, Redlands, CA.

Moore, R., Tindall, I. & Fortune, D. 2004 Update on the HarmonIT Project, the OpenMI standard for modeling. In *Proceedings of 6th International Conference on Hydroinformatics, Singapore, 21–24 June* (ed. S.-Y. Liong, K. K. Phoon & V. Babovic). World Scientific Publishing Company, Singapore, pp. 1811–1818. Available at: http://www.harmonit.org/docs/ harmonit_hydroinformatics_2004_update_moore_tindall_ fortune.doc, last visited in December 2005.

National Observatory of Athens (NOA) 2001 *Telematics Assisted Handling of Flood Emergencies in Urban Areas*. Final Report EN4003, TELEFLEUR, Version No. 2.

Price, R. K. 2000 Hydroinformatics and urban drainage: an agenda for the beginning of the 21st century. *J. Hydroinf.* **2** (2), 133–147.

Robayo, O. 2005 *Map2Map: Converting a NEXRAD Rainfall Map into a Flood Inundation Map*. Dissertation, The University of Texas at Austin, Austin, TX.

Robayo, O., Whitaker, T. & Maidment, D. 2004 Converting NEXRAD map to floodplain map. In *Proceedings of the AWRA*

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest

*Specialty Conference on GIS and Water Resources III, Nashville, TN, 17–19 May*. CDROM. AWRA, Middleburg, VA.

Roberts, A. M. & Moore, R. V. 1998 Data and databases for decision support. *Hydrol. Process.* **12** (1998), 823–834.

US Army Corps of Engineers (USACE) 1987 *HECLIB, Programmers Manual* CPD-58. Hydrologic Engineering Center, Davis, CA.

US Army Corps of Engineers (USACE) 1991 *HECLIB,* vol. 2. *HEC-DSS Subroutines, Programmers Manual* CPD-57. Hydrologic Engineering Center, Davis, CA.

US Army Corps of Engineers (USACE) 1995 *HEC-DSS, User's Guide and Utility Manuals, User's Manual* CPD-45. Hydrologic Engineering Center, Davis, CA.

US Army Corps of Engineers (USACE) 2000 *Hydrologic Modeling System, HMS, Technical Reference Manual* CPD-74B. Hydrologic Engineering Center, Davis, CA.

US Army Corps of Engineers (USACE) 2002 *HEC-RAS River Analysis System, Hydraulic Reference Manual* CPD-69. Hydrologic Engineering Center, Davis, CA.

Vieux, B. E. 2001 *Distributed Hydrologic Modeling Using GIS*. Kluwer, Dordrecht.

Vivoni, E. R. & Richards, K. T. 2005 Integrated use of GIS-based field sampling and modeling for hydrologic and water quality studies. *J. Hydroinf.* **7** (4), 235–250.

Whitaker, T. L. 2003 *Creating Flood Inundation Map from a Rainfall Map*. Draft. The University of Texas Austin, Austin, TX.

Whitaker, T. L. 2004 *Geographically Integrated Hydrologic Modeling Systems*. Dissertation, The University of Texas at Austin, Austin, TX.

Whitaker, T., Maidment, D. R. & Robayo, O. 2004 *Model Integration Through Exchange of Time Series at Information Exchange Points*. Report (Draft), Center for Research in Water Resources, University of Texas at Austin, Austin, TX.

Wolter, R. 2001 *XML Web Services Basics*. Available at: http://msdn.microsoft.com/webservices/webservices/understanding/webservicebasics/default.aspx?pull = /library/en-us/dnwebsrv/html/webservbasics.asp, last visited in September 2005.

Xu, Z. X., Ito, K., Schultz, G. A. & Li, J. Y. 2001 Integrated hydrologic modeling and GIS in water resources management. *J. Comput. Civil Engng. ASCE* **15** (3), 217–223.

Downloaded from https://iwaponline.com/jh/article-pdf/9/2/123/392868/123.pdf
by guest