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2001

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Journal of Hydrologic Engineering, Vol. 6, No. 6, November/December, 2001.

GIS AND DISTRIBUTED WATERSHED MODELS. II: MODULES, INTERFACES, AND MODELS

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ABSTRACT: This paper presents representative applications and models that can take advantage of spatially distributed data in a geographic information system (GIS) format for watershed analysis and hydrologic modeling purposes. The intention is to inform hydrologic engineers about the current capabilities of GIS, hydrologic analysis modules, and distributed hydrologic models, and to provide an initial guide on implementing GIS for hydrologic modeling. This paper also discusses key implementation issues for individuals and organizations that are considering making the transition to the use of GIS in hydrology. Widespread use of GIS modules and distributed watershed models is inevitable. The controlling factors are data availability, GIS-module development, fundamental research on the applicability of distributed hydrologic models, and finally, regulatory acceptance of the new tools and methodologies. GIS modules and distributed hydrologic models will enable the progression of hydrology from a field dominated by techniques that require spatial averaging and empiricism to a more spatially descriptive science.

INTRODUCTION

Many agencies and firms have made significant investments in geographic information system (GIS) technology. Successful implementation of GIS-based tools in hydrologic analysis and modeling depends to a large extent on realistic expectations of what this transition will achieve. The primary objective of this paper is to describe, in a general sense, some of the GIS-based hydrologic applications that are in use. This description is valuable to engineers and engineering companies that are considering increased use of geospatial data and spatially distributed modeling approaches.

The first category of applications discussed consists of GIS modules, which are used to perform geospatial analysis of watershed and hydrologic variables for use in some modeling or predictive context. The second category of applications consists of models that can take advantage of geospatially derived watershed characteristics to make predictions or forecasts of hydrologic variables such as the runoff of water, sediment, and contaminants, or other watershed hydrologic variables such as soil moisture or flood stage. Models considered for discussion all have formulations that take advantage of geospatial information, are widely cited in the literature, and are used for practice or research or both. No distinction is made between physically based and conceptual models. This paper also outlines issues related to successful implementation of GIS-based hydrologic analysis tools. This paper ends with a brief discussion of current trends and future developments in GIS module and distributed hydrologic models.

REVIEW OF LITERATURE

GIS utilities have been used for >10 years for the pre- and postprocessing of spatially distributed hydrologic modeling data. The influence of spatial aggregation on runoff was examined by Mancini and Rosso (1989), who investigated the spatial variability of the Soil Conservation Service (SCS) curve number using a raster GIS and a distributed hydrologic model. Johnson (1989) demonstrated the range of application of GIS functions for hydrologic modeling with the MAPHYD package. That work showed that compatible data sets on terrain and radar-rainfall data could be fully integrated into a watershed modeling system. Stuebe and Johnston (1990) compared the performance of GIS-derived results with manually crafted methods of runoff calculation using the SCS curve number approach. The GIS method was found to be an acceptable alternative, greatly simplifying data preparation and processing.

In a review of water quality and quantity modeling and GIS applications in water resources, Vieux (1991) used a GIS-based triangulated irregular network (TIN) to process the terrain data from a small watershed for application of a finite-element runoff model. Rewerts and Engel (1993) developed a hydrologic toolbox to prepare spatial data for input in the Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model. The impact of land-use changes due to off-road vehicle traffic on the hydrologic response of watersheds was examined by Doe et al. (1995) using the Geographic Resource Analysis Support System (GRASS) GIS for the creation of watershed disturbance scenarios, in conjunction with the CASCade of planes, 2D (CASC2D) (Julien et al. 1995; Ogden 1998) physically based, distributed-parameter hydrologic model.

The U.S. Department of Agriculture (USDA) Water Erosion Prediction Project (WEPP) model was used in conjunction with the GRASS GIS (Savibi et al. 1995) to simulate the response of a watershed in Indiana. GRASS functions were used to estimate parameters for the WEPP model. Results show that GIS greatly simplifies model set up, and that the use of GIS actually improves model performance. Zollweg et al. (1996) developed a GRASS GIS integrated physical-conceptual modeling approach for simulating catchment response.

The utility of GIS for hydrologic analysis was examined by DeVantier and Feldman (1993). These authors concluded that at that time there was no clear evidence that GIS techniques are inherently superior to traditional methods. Furthermore they stated that distributed physically based hydrologic models

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Note. Discussion open until May 1, 2002. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 7, 2000; revised June 5, 2001. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 6, No. 6, November/December, 2001. ©ASCE, ISSN 1084-0699/01/0006-0515–0523/$8.00 + $.50 per page. Paper No. 22287.

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had not been shown to be intrinsically better than lumped-parameter hydrologic models. However, the authors indicated that this is largely because of the lack of application experience, which points to the need for extensive further research and education in GIS-based hydrological methods.

Maidment (1991) identified four distinct hydrologic applications of GIS: hydrologic assessment, hydrologic parameter determination, hydrologic model set up using GIS, and hydrologic modeling inside GIS. In the assessment level, hydrologic factors pertaining to some situation are mapped in GIS. Hydrologic parameter determination involves the analysis of terrain, land-cover, and land-use data to assign relevant parameter values. In his description of hydrologic modeling inside GIS, Maidment (1991) limited such operations to steady-state processes. It was suggested, however, that with developing space-time data structures in GIS, it would be realistic to begin thinking about performing unsteady numerical modeling within GIS.

Hydrologic assessment refers to the use of GIS for the analysis of various hydrologic factors for the purpose of assessing risk or susceptibility to pollution. One example of this type of analysis is the use of GIS for evaluating groundwater contamination potential using the DRASTIC ranking technique developed by the U.S. EPA (Evans and Myers 1990). Other examples of the non-point-source assessment techniques are described by DeBarry (1991) and Hamlett et al. (1992). This type of spatial modeling is not based upon a rigorous simulation of physical, chemical, or biological processes; rather, it uses weighted indexing schemes to quantify the relative influence of various factors in contributing to pollution problems.

Parameter estimation is probably the most active area in the GIS field related to hydrology. In this case, the objective is to determine and quantify parameters that can be used as input to hydrologic models through the manipulation and analysis of various terrain-related data sets. Reported in the literature are numerous examples where information on land slope, channel slope, soil characteristics, and land cover was derived from digital raster and vector data layers for this purpose [e.g., DeBarry and Carrington (1990), Peterson and Hamlett (1998), Yagow and Shanholtz (1996), and Ross and Tara (1993)]. One way in which a GIS can be used to derive hydrologic parameters is by linkage to a library of georeferenced parameter values. For example, the Simulator for Water Resources in Rural Basins–Water Quality version (SWRRBWQ) model has a library of weather parameters defined for about 100 weather stations in the United States so that estimates of required climatic variables can be extracted automatically for modeling purposes (Arnold et al. 1990). Likewise, for soils information, SWRRBWQ has detailed data on soil properties for hundreds of soil types as depicted on county-level SCS soil maps. Similar default parameterization approaches are also used for the Soil and Water Assessment Tool (SWAT) model, which is the successor to the SWRRB serious of models. Descriptions of how GIS has been used to automate the parameterization process for these particular models have been provided by Evans et al. (1992), Rosenthal et al. (1993), and Bian et al. (1995).

It is also possible to perform varying degrees of hydrologic modeling directly within a GIS, so long as temporal variability is not an issue. This is the case when considering annual averages of variables such as annual average flow or pollutant loadings from a watershed. For example, one could implement spreadsheet-type models in which flows or loadings are computed as flow or load per unit area, as demonstrated by Evans et al. (1994) and Nizeyimana et al. (1997). One could also capture some more complex equations, such as those for pollutant loadings derived by means of regression, where the independent variables in the regression equations are mapped in coverages and then the loadings are worked out based on mathematical combination of coverage data. Another way of eliminating time as a variable is to take a snapshot at the peak flow condition and model that by assuming the discharge is at peak value throughout the system (Chieng and Luo 1993). It is thus possible to route water through GIS networks using analogies to traffic flow routing in which each line segment is assigned an impedance measured by flow time or distance and flow is accumulated going downstream through the network.

To date, a number of researchers have written unsteady, distributed-parameter, hydrologic models within GIS. This development has tended to focus on the GRASS GIS because of the availability of source code. Models incorporated into GRASS to date include the Agricultural Non-Point-Source Pollution Modeling System (AGNPS) (Young et al. 1989), ANSWERS, TOPMODEL, WEPP (USDA), r.water.fea (Vieux and Gaur 1994), and r.hydro.CASC2D (Ogden and Saghafian 1995).

GIS MODULES FOR HYDROLOGIC DATA PROCESSING

The following modules are discussed in alphabetical order. Each is briefly discussed to give the reader an idea of current capabilities. For more in-depth information, see the full Task Committee report (DeBarry et al. 1999) or other cited references.

ARC/INFO Hydrologic Routines

The ARC/INFO GIS from Environmental Systems Research Institute (ESRI), Redlands, Calif., contains a number of functions that are useful to hydrologists in addition to a large number of geospatial data processing and coordinate conversion routines. The majority of these functions are within the GRID spatial modeling software. GRID is a component of the ARC/INFO suite of software tools. GRID is a raster- or cell-based geoprocessing toolbox that is integrated with ARC/INFO. The FLOWDIRECTION function creates a new grid of flow directions from each cell to the steepest downslope neighbor, given an elevation grid as input. The FLOW ACCUMULATION function calculates the amount of upstream area or cell weighted flow that drains into each cell. The WATERSHED function will delineate the entire upstream area that drains into a user supplied set of basin outlet cells. The SLOPE, ASPECT, and CURVATURE functions calculate the slope, azimuth, and curvature of each cell. The GRID software is capable of finding upstream or downstream flow paths from any cell in a digital elevation model (DEM) and the length of those flow paths, delineating stream networks, and ordering the stream network with both the Strahler and Shreve methods.

The majority of the analysis functionality of GRID also is available within the ArcView Spatial Analyst, the ESRI's desktop GIS product. The combination of all the individual tools and functions for hydrologic work plus the framework of programming languages in which to embed the analytical tools provides a powerful GIS environment for the hydrologic community.

GRASS

GRASS (*GRASS* 1993) is a public domain raster GIS initially developed by the Environmental Division of the U.S. Army Construction Engineering Research Laboratory as a general-purpose spatial modeling and analysis package. GRASS development is now being directed by the Center for Applied Geographic and Spatial Research at Baylor University (Internet site at ⟨http://www.baylor.edu/∼grass/⟩). GRASS is highly interactive and graphically oriented, providing tools for developing, analyzing, and displaying spatial information.

GRASS runs through the use of standardized command line input or under the X Window system under the UNIX/Linux environment. Though GRASS is raster based, it can also deal with vector (linear features) or point data. New maps can be digitized or scanned. Maps also can be transferred from other GIS systems such as ARC/INFO. Data files can be developed for large or small geographic regions at any scale desired within the limits of the source data and the storage capacity of the hardware.

GRASS was successfully coupled with a number of hydrological and water quality models, including ANSWERS, AGNPS, TOPMODEL, SWAT, and SWIM (Rewerts and Engel 1991; Srinivasan and Engel 1991; Chairat and Delleur 1993; Srinivasan and Arnold 1994; Krysanova et al. 1996), to facilitate input of spatially distributed information and enhance the use and utility of the models.

The raster formulation of GRASS is very attractive for use in spatially distributed hydrological modeling, because spatial data can easily be translated from the GIS to the model to initialize it and the model outputs can go back to GIS again for visualization purposes. Second, GRASS is a public domain GIS; it may be downloaded free of charge and all program source code is freely available. This is different from other proprietary GIS packages, such as ARC/INFO, and significantly facilitates further software development. Third, GRASS is written in the C programming language, which is also widely used for modeling. Fourth, GRASS is flexible enough for a variety of applications, as soon as data layers can be transported to and from several other GIS, including ARC/INFO. Last, but not least, GRASS has specific programs for hydrologic modeling and interpolation, which can be very useful.

The GRASS program r.watershed is the main tool for delineation of basin and subbasin boundaries from a DEM. Other hydrologically oriented programs exist in GRASS, such as r.basins.fill, r.cost, and r.drain, as well as the useful interpolation tools. There are a number of transformation programs between GRASS and various other formats: DLG (v.import), DLG-3 (v.in.dlg and v.out.dlg), ASCII (v.in.ascii, v.out.ascii, r.in.ascii. and r.out.ascii), DXF (v.in.dxf and v.out.dxf), ARC/INFO (v.in.arc and v.out.arc), and MOSS (v.out.moss).

GIS/HEC-1 Interface Module (Prince William County Model)

The use of mathematical models such as HEC-1, TR-20, ILLUDAS, SWMM, HSPF, PSRM-QUAL, and VAST has greatly enhanced the hydrologic engineering field through efficiency and flexibility. However, these models still require intensive data development for input such as time of concentrations, lags, SCS curve numbers, and channel routing parameters. The use of the GIS to aid in developing this input data, such as overlaying hydrologic soil groups with land use to develop composite SCS curve numbers, is well documented (DeBarry and Carrington 1990). A program developed and described by DeBarry (1996) aids in hydrologic modeling for storm-water management analysis, flood prediction, reservoir and detention basin sizing, and development cause/effect scenarios. It aids in placement of regional detention facilities by reducing the effort required to determine the most efficient location. The program has a non-point-source pollution prediction component that will aid in best management practice placement, monitoring station locations, and National Pollutant Discharge Elimination System compliance.

The Prince William County Model uses contoured elevation data that are converted to 6.1-m^2 (20-ft^2) grids for use in the time-of-concentration calculations. Digital hydrologic soil group coverages are used with a relational look-up table to link specific soils polygons to the hydrologic soil group classification and other relative interpretive data associated with each soil type. Land-use data from a variety of sources are tailored to reflect the land-use classifications used in TR-55. ARC/INFO's coverage polygons are converted to 6.1-m^2 (20-ft^2) grids for the computations.

The process to automate data set creation for a watershed hydrologic model (such as HEC-1, TR-20, or PSRM) involves first creating GIS coverages for soils, land use, and subwatershed boundaries, and assigning attributes to each coverage such as hydrologic soil groups and TR-55 land-use classifications. Coverages (hydrologic soil groups and land use) are overlayed to compute CN for each polygon. Time-of-concentration and SCS lag are computed for user-defined subareas based upon the SCS TR-55 method. ESRI's GRID package is used for this purpose. The interface allows the user to pinpoint a downstream analysis point. The macro within GRID uses DEM information to obtain slope steepness, Manning's *n* value, and time of concentration.

The application will compute non-point-source pollutant loading based on land use and soil type using the National Urban Runoff Program data and is able to compute the loading by parcels, subarea, and watershed. The National Urban Runoff Program data are supplied in a look-up table, with source values modifiable if actual field data from local stations are available. The results meet the requirements of the U.S. EPA's National Pollutant Discharge Elimination System program. The program computes daily, monthly, and annual loads. Water quality parameters incorporated include total suspended solids, pH, total dissolved solids, total Kjeldahl nitrogen, COD, nitrate plus nitrite, biochemical oxygen demand, dissolved phosphorus, oil and grease, total ammonia plus organic nitrogen, fecal coliform, total phosphorus, and fecal streptococcus.

The Prince William County Model realizes the economics and efficiency of using a GIS in the process of fully automating watershed hydrologic model input data development and, at the same time, produces high quality graphics for reports and public meetings. The GIS software used in this study is a combination of workstation ARC/INFO, with GRID, and PC ARC/INFO (ESRI). The macros have been tested and verified on three different watersheds.

HEC-GeoHMS

HEC-GeoHMS [Hydrologic Engineering Center (HEC) 2000] is a geospatial hydrologic modeling extension software package that uses a graphical user interface and is linked to the ArcView and Spatial Analyst GIS. HEC-GeoHMS uses DEM data to determine drainage paths and watershed boundaries and transforms them into hydrologic data structures representing the watershed response to rainfall events. The current version of HEC-GeoHMS creates a background map file, lumped basin model, grid-cell parameter file for use in running the HEC-HMS hydrologic model discussed in the next section of this paper.

HECPREPRO and CRWR-PrePro

HECPREPRO (Hellweger and Maidment 1999) and CRWR-PrePro (Olivera and Maidment 2000) were developed at the Center for Research in Water Resources (CRWR) of the University of Texas at Austin to support HMS. These programs are used to establish the topology of hydrologic elements and prepare a basin-input file for HEC-HMS modeling.

TOPographic PArameteriZation (TOPAZ)

TOPAZ is a software package for automated digital landscape analysis (Garbrecht and Martz 1997). Automated landscape analysis is a very challenging problem (Hayes 2000). The TOPAZ program uses a raster DEM to identify and measure topographic features, define surface drainage, subdivide watersheds along drainage divides, quantify the drainage network, and parameterize subcatchments. TOPAZ is designed primarily to assist with topographic evaluation and watershed parameterization in support of hydrologic modeling and analysis. It can also be used to address a variety of geomorphological, environmental, and remote sensing applications.

The overall objective of TOPAZ is to provide a comprehensive evaluation of DEMs, with particular emphasis on maintaining consistency between all derived data, the initial input topography, and the physics underlying energy and water flux processes at the landscape surface. A number of the limitations of existing DEM processing methods with respect to drainage identification in depressions and over flat surfaces have been overcome in TOPAZ, and a number of new features have been added to address specific hydrologic and hydraulic needs (Garbrecht and Martz 1995). TOPAZ is not a GIS in the traditional sense. It is a system of software modules that performs the numerical processing of raster DEMs and produces numerous data layers and attribute tables. For data layer algebra and monitor display capabilities, TOPAZ relies on a user-selected GIS. The interface to a GIS is provided through generated raster files. The analytical operations performed by TOPAZ achieve three broad functions: (1) elevation data preprocessing (treatment of depressions and flat areas); (2) hydrographic segmentation (definition of surface drainage, channel network, and subcatchments); and (3) topographic parameterization, which includes quantification of network and subwatershed properties and parameters.

The output from TOPAZ consists of report files, evaluation files, tables, and raster data. Report files provide a summary of the program execution for each module and include a listing of the input and user options, tasks performed by the modules as they are completed, and warning and error messages. Evaluation files print the results of specific evaluations such as the statistics of the channel links or subcatchments. Tables provide lists of attributes for channel links and subcatchments. They contain data that are often needed in hydrologic applications and distributed models of land-surface processes. Rasters represent data layers of spatial topographic, network, and subcatchment attributes. These rasters can be imported into a GIS for display, overlay analysis, and further processing.

Watershed Modeling System (WMS)

The Watershed Modeling System (WMS) was developed specifically for engineers and its sole purpose is to set up mathematical watershed hydrologic models (Nelson et al. 1994). The WMS is a graphically based, comprehensive hydrologic modeling environment that is designed to take advantage of watershed data developed or stored in GIS. Although it is neither a complete GIS itself nor an extension created with GIS macros or programming languages, it is capable of creating, reading, and writing GIS data layers using the shape file format.

Although there have been many advances in the development of mathematical computer models that simulate the rainfall-runoff process in a spatially distributed manner, lumped parameter models such as HEC-1, TR-20, SWMM, and others continue to be the accepted standard by most regulatory agencies. WMS was developed to derive inputs for traditional models such as HEC-1 and TR-20 from GIS data. At the same time, WMS provides interfaces to some of the emerging spatially distributed models being developed by the U.S. Army Corps of Engineers, Engineer Research and Development Center. One such model is CASC2D (Julien et al. 1995; Ogden 1998).

WMS can be used in a stand-alone mode without GIS. However, WMS is compatible with different GIS data structures, including vector coverages, grids, and TINs. Data at different stages of development can be transferred between WMS and a GIS. Complete interfaces for several different models, both lumped parameter and spatially distributed, are available.

WMS was originally developed to automatically delineate watershed and subbasin boundaries with TINs (Nelson et al. 1994); the latest release includes the capability to delineate watersheds with gridded DEMs or use vector coverages of previously delineated basin boundaries and stream networks stored in a GIS format. WMS can also process both grid (raster) and vector data for land use, soil type, rainfall zone, and flow path networks in order to develop important modeling parameters such as curve numbers, infiltration parameters, rainfall intensities, and water course travel times (lag time and time of concentration).

WMS is a comprehensive hydrologic modeling environment developed system designed by and for hydrologic engineers. WMS operates both as stand alone and in combination with GIS data, making it versatile enough to accommodate all hydrologic modeling applications. The strength of WMS is that it includes all options for each supported hydrologic model, reducing uncertainties associated with model set up and decreasing model set-up time. The progression of steps required for setting up each hydrologic model is highlighted by intelligent ordering of menu options within the interface.

DISTRIBUTED WATERSHED MODELS

The following distributed watershed models are discussed in alphabetical order. Each model discussed is widely used for practice or research or both. Models are briefly discussed to give the reader an idea of current capabilities. These models use geospatial information and have varied formulations that are applicable over a wide range of watershed sizes and for different purposes. For more in-depth information, see the full Task Committee report (DeBarry et al. 1999) or other cited references.

AGNPS 98

The AGNPS 98 pollutant loading modeling environment was developed jointly by the USDA Agricultural Research Service and Natural Resources Conservation Service (Binger and Theurer 2001). AGNPS 98 comprises several modules that enable users to develop appropriate input parameters for evaluations of best management practices using simulations for their watershed systems. AnnAGNPS is the pollutant loading module designed for risk and cost/benefit analyses. The model was developed to simulate long-term sediment and nutrient transport from agricultural watersheds using a daily time step. The basic modeling components are hydrology, sediment, nutrient, and pesticide transport. Homogeneous land area (cell) geometric representations of a watershed are used to provide landscape spatial variability. The physical or chemical constituents are routed from their origin within a cell and are either deposited within the stream channel system or transported out of the watershed. Pollutants can then be identified at their source and tracked as they move through the watershed system. Runoff of water is calculated using the runoff curve number, and sediment runoff is estimated using the revised universal soil loss equation. Special components are included to handle concentrated sources of nutrients (feedlots and point sources), concentrated sediment sources (gullies), and added water (irrigation). Output is expressed on an event basis for selected stream reaches and as source accounting (contribution to outlet) from land or reach components over the simulation period.

Channel evolution is modeled with AGNPS 98 using the USDA Agricultural Research Service Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) model, which simulates unsteady, 1D flow, graded-sediment transport, bank erosion processes, and pollutant transport in watershed channels, incorporating in-stream hydraulic structures and nonstructural remediation measures. Stage-discharge relationships are computed using the diffusion wave method. CONCEPTS simulates transport of suspended- and bed-load sediments selectively by size classes. Channel boundary roughness and bank stability affected by riparian vegetation are included in CONCEPTS.

CASC2D

The hydrologic model CASC2D uses a square-grid, infiltration-excess formulation that solves the equations of transport of mass, energy, and momentum between model grid cells using finite differences (Julien et al. 1995; Ogden and Julien 2001). The model is fully unsteady and spatially varied. The purpose of CASC2D is to perform detailed scientific and engineering analyses of watersheds where the spatial variability of watershed characteristics and rainfall are important. Use of CASC2D is also prescribed when the user is interested in modeling processes at the subcatchment scale or when small-scale output is desired at internal catchment locations, such as street flooding, in urbanized watersheds.

The CASC2D formulation is continuous and includes evapotranspiration, rainfall input, rainfall interception (Gray 1973); Green and Ampt (1911) or Green and Ampt with redistribution infiltration (Ogden and Saghafian 1997), 2D diffusive-wave overland flow routing (Julien et al. 1995), 1D diffusive-wave channel flow routing in natural cross sections (Ogden 1994), empirical overland erosion (Kilinc and Richardson 1973), overland sediment transport and deposition (Johnson et al. 2000), and bed- and suspended-load sediment routing in channels (Ogden and Heilig 2001).

CASC2D development originated at Colorado State University through funding by the U.S. Army Research Office. Recent enhancements to the model at the University of Connecticut and the U.S. Army Corps of Engineers, Engineer Research and Development Center, have improved model generality. The model has been applied to simulate watersheds from 0.016 to 2,300 km^2 in area with considerable success. CASC2D models have been developed with grid sizes ranging from 10 to 1,000 m. The model is typically applied at grid sizes ranging from 30 to 125 m. CASC2D can be run in a single-event mode or in a continuous (multievent) mode. Continuous simulations can be run for an indefinite period of time.

Input data requirements for the model include DEM topography; rainfall rates from gauges, weather radar, or meteorological model; meteorological variables for continuous simulations (air temperature, relative humidity, wind speed, and solar radiation); channel cross sections; overland and channel flow roughness coefficients; soil hydraulic properties; and initial soil moisture content. Default output from CASC2D includes an outflow hydrograph at the watershed outlet and a summary file containing details of the simulation mass balance. Optional output includes sediment (suspended- and bed-load) hydrographs at the catchment outlet; flow and sediment hydrographs at internal catchment locations; and time series of spatially varied output maps of overland flow depth; channel flow depth, overland erosion/deposition, and land-surface soil moisture.

A rigorous calibration and verification of CASC2D on a 21-km^2 research watershed was demonstrated by Senarath et al. (2000). This study revealed that CASC2D is capable of making reasonably accurate runoff predictions at internal locations once calibrated at the watershed outlet. This conclusion requires that sufficient data are available for model calibration. The sensitivity of CASC2D to uncertainties in land-surface characteristics and rainfall was evaluated by Ogden et al. (2000) using data from the catastrophic flash flood that impacted Fort Collins, Colo., in July 1997. Results showed that CASC2D provides accurate runoff predictions in an urbanized watershed under the action of extreme rainfall. Uncertainties in land-surface parameters have a small effect compared to errors in rainfall input. For this reason, the use of WSR-88D radar-rainfall estimates with a model such as CASC2D should be done in conjunction with rain gauge verification.

The CASC2D model uses SI units and the Universal Transverse Mercator (UTM) map projection system. The model is supported by the U.S. Department of Defense WMS hydrologic model interface developed at Brigham Young University, Provo, Utah. WMS has import/export capabilities with both ARC/INFO and GRASS GISs. The WMS contains specific functionality for creating CASC2D input data sets including topographic analysis using TOPAZ (Garbrecht and Martz 1997), stream cross-section preprocessor, stream profile smoothing tools, and map creation/manipulation capabilities. WMS and GIS are not required for using CASC2D but are helpful for data set creation. The WMS can also be used to visualize CASC2D output using an output map viewer and film loop feature.

HEC-RAS and HEC-HMS

The HEC of the U.S. Army Corps of Engineers is the developer of a number of widely used hydraulic and hydrologic computer models, including the widely used HEC-1 runoff model and HEC-2 river hydraulics model. Numerous companies, universities, and public institutions have developed GIS linkages for these models. Most of these efforts have taken the form of preprocessors that prepare input files for the models or postprocessors that read model output files. HEC is in the process of a major software modernization effort, called NexGen (HEC 1993) directed at replacing batch-style programs such as HEC-1 and HEC-2 with interactive programs. HEC-1 has been superceded by a new program called HEC-HMS, and HEC-2 has been superceded by HEC's river analysis system (HEC-RAS). Although the old programs will be supported for the foreseeable future, there will be no new versions of HEC-1 or HEC-2 and improvements and new features will be added only to the new programs. HEC's model development philosophy with respect to GIS is that new programs should take advantage of geospatial data from GIS/computer-aided design and drafting programs but should not depend on those programs for execution. HEC models can exchange data with many GIS programs but do not depend on proprietary data formats.

HEC-RAS can import HEC-2 input files, so preprocessors designed to work with HEC-2 could also be used with HEC-RAS. However, HEC-RAS version 2 has an expanded set of import and export functions to preserve location data (HEC 1997). Geospatial outputs from HEC-RAS include cross sections—2D cut lines, with water surface elevations for one or several profiles, and water surface bounds for each reach. Output cross-section data can be read into a GIS layer together with water surface elevations between the cross sections. Inundated areas can be mapped by comparing the interpolated water surface with the ground surface.

A GIS can be used to prepare input parameters for the modified Clark unit hydrograph conceptual routing method used in HEC-HMS. HEC-HMS is designed to work with gridded precipitation data, such as National Weather Service WSR-88D radar-rainfall estimates. The model requires a small number of parameters for each watershed grid cell.

Modular Modeling System–Precipitation Runoff Modeling System (MMS/PRMS)

The interdisciplinary nature and increasing complexity of environmental and water resource problems require modeling approaches that can incorporate knowledge from a broad range of scientific disciplines. Selection of a model to address these problems is difficult given the large number of available models and the potentially wide range of study objectives, data constraints, and spatial and temporal scales of application. Coupled with this are the problems of characterizing and parameterizing the study area once the model is selected. Guidelines for estimating parameters are few and the user commonly has to make decisions based on an incomplete understanding of the model developer's intent. To address the problems of model selection, application, and analysis, a set of modular modeling tools, the MMS (Leavesly et al. 1996), was developed by the U.S. Geological Survey using modules originally developed for the PRMS (Leavesley et al. 1996). The PRMS has been applied to a variety of watersheds since its development in the mid-1980s. MMS uses a master library that contains compatible modules for simulating a variety of water, energy, and bio-geochemical processes. A model is created by selectively coupling the most appropriate process algorithms from the library to create an integrated model for the desired application. Where existing algorithms are not appropriate, new algorithms can be integrated by the user. A GIS interface is used to characterize topographic, hydrologic, and ecosystem parameters; visualize spatially and temporally distributed model parameters and variables; and validate model results.

MMS provides a flexible framework in which to develop a variety of physical process models that can be coupled with resource-management models for use in addressing a wide range of management issues. The conceptual framework for MMS has three major components: preprocess, model, and postprocess. The preprocess component includes the tools used to prepare, analyze, and input spatial and time-series data for use in model applications. The model component includes the tools to build a model by selectively linking process modules from the module library. The library can contain several modules for a given process, each representing an alternate approach to simulating that process. The postprocess component includes tools to display and analyze model results and to pass results to management models or other types of software. Spatial data analysis is accomplished using GIS tools that have been developed and tested in both ARC/INFO and GRASS.

Postprocessing of MMS output is done using statistical and graphical analysis procedures that provide a basis for comparing module performance, to aid in making decisions regarding the most appropriate modeling approach for a given set of study objectives, data constraints, and temporal and spatial scales of application. A GIS interface provides tools to display spatially distributed model results and to analyze results within and among different simulation runs.

Systéme Hydrologique Européen (SHE)

SHE (Abbott et al. 1986) was initially developed in several research institutes across Europe as part of a joint initiative. In its original form, the model structure closely matched that proposed by Freeze and Harlan (1969), the only discernible difference being that, in SHE, water was assumed to only flow vertically in partially saturated soils. Subsequent developments of SHE conducted at two European research institutes have resulted in two versions of the model: SHETRAN, developed at the University of Newcastle upon Tyne, U.K., and MIKE-SHE, developed at the Danish Hydraulics Institute. These later versions of SHE not only model the hydrology of watersheds but also model solute and sediment transport. The main difference between the two versions is in their treatment of flow in the subsurface; SHETRAN is capable of modeling 3D flow in variably saturated soils (Parkin 1996), whereas MIKE-SHE simulates only vertical flow in partially saturated soils. Both versions have sophisticated, graphical user interfaces that allow the user to input, manipulate, and output spatially distributed data and to visualize the temporal evolution of 3D model predictions.

SWAT

The SWAT model has a conceptual formulation and is used to assess water supplies and non-point-source pollution on small watersheds and large river basins. A detailed description of the model is given in Arnold et al. (1998). The SWAT formulation includes land management, water quality loadings, flexibility in basin discretization, and continuous simulations. SWAT was designed to simulate the major components of the hydrologic cycle and their interactions as simply and realistically as possible (Arnold and Allen 1996) and to use inputs that are readily available over large areas so that the model can be used in routine planning and decision making.

Model components include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Simulated hydrologic processes include surface runoff using the SCS curve number of Green and Ampt (1911) infiltration equation, percolation modeled with a layered storage routing technique combined with a crack flow model, lateral subsurface flow, groundwater flow to streams from shallow aquifers, potential evapotranspiration, snowmelt, transmission losses from streams, and water storage and losses from ponds. Weather variables can be provided as inputs or artificially generated based on monthly climate statistics.

Sediment yield is computed for each subbasin with the modified universal soil loss equation. Soil temperature is modeled in layers, and crop growth is simulated. Nitrate losses in runoff, percolation, and lateral subsurface flow, as well as nitrogen fate and transport, are simulated. The nitrogen transformation model includes residue mineralization, humus mineralization, nitrification, denitrification, volatilization, fertilization, and plant uptake. Pesticide transformations are simulated with a simplification of the GLEAMS model approach.

Stream processes considered in SWAT include channel flow routing, sediment routing, and nutrient and pesticide routing and transformation modified from the QUAL2E model. The ponds and reservoirs component contains water balance, routing, sediment settling, and simplified nutrient and pesticide transformation routines. Water diversions into, out of, or within the basin can be simulated to represent irrigation and other withdrawals from the system.

A GRASS GIS interface was developed for SWAT (Srinivasan and Arnold 1994). The input interface automatically subdivides a basin (grids or subwatersheds) and then extracts model input data from map layers and associated relational databases for each subbasin. The output interface allows the user to display output maps by selecting a subbasin from a GIS map. An ArcView GIS interface for SWAT consists of three key components: (1) preprocessor generating subbasin topographic parameters and model input parameters; (2) editing input data and execute simulation; and (3) postprocessor viewing graphical and tabular results.

The U.S. EPA is incorporating SWAT into the BASINS interface for assessment of impaired water bodies. BASINS is an interface developed in ArcView to allow state regulatory agencies the ability to quickly analyze water quality problems.

TOPMODEL

TOPMODEL (Beven and Kirkby 1979), developed at the University of Lancaster, U.K., has a physical/conceptual formulation that uses a semidistributed approach. The watershed is partitioned, on the basis of a topographic index, into regions that are deemed to behave in a hydrologically similar manner. The model was originally developed for rainfall-runoff modeling in upland temperate catchments with coarse soils or low intensity rainfall, where the saturation–excess runoff production mechanism is dominant. One of the appealing features of the model is that it uses a small number of parameters, is computationally efficient, and can be used to give an indication of the spatial distribution of soil moisture in a watershed. The simple structure of this model allowed Stuart and Stocks (1993) to encode it into a GIS.

The formulation of TOPMODEL is based on a factor known as the topographic index (Beven and Kirkby 1979). Regions within the catchment with similar topographic indices are assumed to behave as hydrologically similar land units. The topographic index is developed from a DEM, and a histogram of the topographic index is used within TOPMODEL to predict saturated regions within the watershed for a given soil moisture state. Spatially varied topographic features are used to develop the topographic index. However, the spatial structure of watershed features and rainfall is not preserved in the model. TOPMODEL has been applied to a large number of catchments, with varying degrees of success. The topographic index is a static quantity that includes no information regarding prior wetting history of the catchment, including hysteresis effects.

GIS IMPLEMENTATION AND MANAGEMENT

The most highly integrated and centrally managed GIS implementation occurs when an organization plans to incorporate GIS technology throughout the entire operation. This is usually a formally planned system, designed to reduce duplication in the organization and allow access to all potential users. When an organization does not depend on GIS for its core business functions, a GIS service center is often developed. In this strategy, a specific GIS group manages the use of the technology throughout the organization. Finally, in specialized applications, management may introduce GIS to an organization in a behind-the-scenes manner. For special applications, a GIS tool may be imbedded in another application familiar to the user.

In recognition of the three implementation approaches outlined above, an organization may determine the need for a hybrid approach to the system. Depending upon such things as finances and skills of the users, management could decide they need to develop a customized implementation where GIS personnel develop some features of the GIS internally and purchase others.

No matter which style of implementation an organization chooses, no approach guarantees a successful transition to GIS. However, it has been observed that successful installations generally share the following characteristics:

- Champion to promote GIS development within the organization
- Planning
- High-level management support
- Completion of a user-needs assessment
- Completion of a prototype pilot project
- Shared project ownership among the users
- Accurate time and cost estimates for associated costs, including products
- Clear goals and objectives defined for the GIS department
- GIS education and training for affected employees and management
- Coordination of GIS development and staff continuity
- Defined funding plan
- Solid written contracts with vendors and clients
- Publicized successes

Information on GIS implementation and management approaches was obtained by Johnson and Dyke (1997) through a review of a variety of organizations, both public and private, large and small. Results of this review as well as other GIS implementation issues are discussed in considerably more detail in the Task Committee report (DeBarry et al. 1999).

FUTURE DIRECTIONS AND NEEDS FOR USE OF GEO-SPATIAL INFORMATION IN ENGINEERING HYDROLOGY

Distributed hydrologic models that fully use spatial data from GIS are reaching maturity, although questions regarding their appropriate application remain in the research arena. There is a growing body of evidence that no hydrologic model is universally applicable. The variety of runoff production mechanisms and the wide range of space scales and timescales studied has necessitated creation of a number of different spatially distributed model formulations. Nonetheless, state and local regulators often insist that traditional modeling approaches be used, perhaps in situations where they are unsuitable. Demonstrated benefits through the application of geospatial technology in the study of hydrology will help remedy this situation.

The increasing availability of spatially distributed topographic, soils, land-use, land-cover, and precipitation data provides the prime motivation for the development, verification, and eventual acceptance of GIS modules and distributed hydrologic models capable of taking full advantage of these new data. New developments must acknowledge the uncertainties inherent in the data and subsequent model parameter assignments. Lumped parameters at the basin scale made sense when data were largely read from paper maps. However, the increasing use of GIS to store watershed characteristics data is forcing hydrologic modelers to spatially aggregate data to the lumped subcatchment scale because the application of lumped models on very small subcatchments is not feasible. This is not to say that all hydrologic predictions require a distributed model. Lumped models will remain valuable tools with many applications. The development of distributed models will allow detailed studies that include the impacts of spatial variability of watershed characteristics and precipitation where necessary, as well as provide spatially distributed output of hydrologic variables.

The recent availability of rainfall rate estimates from the WSR-88D weather radar network is an exciting development in engineering hydrology. In the pre-NEXRAD era, a hydrologic modeler could be quite confident that little or no rainfall data were available for a particular catchment under study. The national network of WSR-88D radars provides near continuous coverage of the entire contiguous United States. The availability of radar-rainfall estimates provides the opportunity to calibrate and verify hydrologic models on catchments that have stream gauges. This fact will spur development and use of models that can take advantage of WSR-88D radar-rainfall estimates.

In the United States, streamflow gauging stations are diminishing in number at a time when most other sources of other types of land-surface and hydrologic data are increasing. With the ever-present importance of the calibration and verification of hydrologic models afforded by availability of rainfall estimates from the WSR-88D system, the decline in streamflow gauging stations is alarming. Gauging stations on smaller watersheds are being deactivated at a disproportionate rate because there are fewer stakeholders at the small basin scale. However, runoff data from smaller watersheds are required for hydrologic model calibration/verification and regionalization of model inputs. The decline in the number of streamflow gauging stations must be halted or the future of hydrologic modeling advancements will be placed in jeopardy.

Perhaps the most pressing reason for developing hydrologic modeling techniques that fully exploit the data-handling capabilities of GIS is to advance beyond the time-tested, but limited, lumped and empirical approaches that permeate the practice of engineering hydrology. Historically, engineering hydrologists have become somewhat comfortable with the uncertainty that comes with the inability to strictly calibrate and verify hydrologic models. The tremendous data-handling capabilities of GIS and improved processing offered by GIS modules allow creation of hydrologic models that can better simulate spatially varied hydrology. GIS technology provides the gateway for the advancement of engineering hydrology from a field dominated by empiricism to a more exact science.

An important GIS hydrology-related area of research is in developing appropriate scaling relationships for spatially distributed hydrologic variables. This research may lead to improved performance of lumped modeling approaches by taking full advantage of fine-scale data in assigning optimal lumped model parameter values.

CONCLUSIONS

The benefits most often associated with the use of GIS in watershed and hydrologic analysis include improved accuracy, less duplication, easier map storage, more flexibility, ease of data sharing, timeliness, greater efficiency, and higher product complexity. In general, GIS systems have been praised for enabling rapid input, storage, and manipulation of geospatial information. However, current GIS technology does not facilitate input, storage, and manipulation of time-varying data in a straightforward way. For this reason, modules and interfaces that exchange data with GIS and allow pre- and postprocessing of time-varying hydrologic model inputs and outputs are popular. GIS-based hydrologic analysis techniques are in various stages of development and are beginning to enter mainstream hydrologic engineering practice. At present, the most widely used techniques are GIS interfaces for traditional models such as HEC-1 and TR-20.

Although spatially distributed models have not yet received widespread acceptance, specialized interfaces linked with GIS have increased model usability. GIS modules and model interfaces will undoubtedly lead to greater use and ultimate acceptance of distributed hydrologic models over the next several years. There is no doubt that in the future hydrologic modeling techniques will increasingly depend upon GIS and geospatial modules and model interfaces.

Comprehensive physically based distributed models such as CASC2D and SHE were at one time thought to be prohibitively cumbersome for anything other than research projects because of their computational expense and input data requirements (Abbott and Refsgaard 1996). This is no longer the case. The widespread availability of spatial data through GIS, high-performance computers, and development of sophisticated user interfaces (e.g., WMS) have made such models far more usable.

Many government agencies and private firms have made large investments in GIS capabilities and in data conversion. The results of organizational adoption of GIS are often mixed because of implementation issues. Successful transition to the use of GIS-based technologies in hydrologic engineering require correspondence between user expectations and actual capabilities.

ACKNOWLEDGMENTS

This set of two papers are the result of the ASCE Water Resources Engineering Division Task Committee on GIS Modules and Distributed Models of the Watershed. Members of the Task Committee, besides the writers of this paper, who contributed to this effort are Thomas A. Evans, Luis Garcia, Jeff Jorgeson, Valentina Krysanova, George Leavesley, David R. Maidment, E. James Nelson, Francisco Olivera, Rafael G. Quimpo, Thomas A. Seybert, William T. Sloan, David Burrows, Edwin T. Engman, Ron Bigner, Barry M. Evans, and Fred Theurer. Their assistance and collaboration are appreciated.

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