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Review of GIS Applications in Hydrologic Modeling

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Review of GIS Applications in Hydrologic Modeling

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Abstract: Geographic information systems (GIS) provide a digital representation of watershed characteristics used in hydrologic modeling. This paper summarizes past efforts and current trends in using digital terrain models and GIS to perform hydrologic analyses. Three methods of geographic information storage are discussed: raster or grid, triangulated irregular network, and contour-based line networks. The computational, geographic, and hydrologic aspects of each data-storage method are analyzed. The use of remotely sensed data in GIS and hydrologic modeling is reviewed. Lumped parameter, physics-based, and hybrid approaches to hydrologic modeling are discussed with respect to their geographic data inputs. Finally, several applications areas (e.g., floodplain hydrology, and erosion prediction) for GIS hydrology are described.

Introduction

The use of computers in hydrologic analysis has become so widespread that it provides the primary source of data for decision making for many hydrologic engineers. Since so much of hydrology is linked to processes at the earth's surface, the connection to the topographic, computer-based methodology known as the geographic information system (GIS) is a predictable step in the evolution of hydrologic engineering. As with many other exercises in computer representations of reality, applications of GIS for the purpose of aiding hydrologic modeling are subject to the skeptical classification of "interesting toys." The purpose of this review is to delineate and assess the progress made in the development of GIS applications in hydrology.

Geographic information systems link land cover data to topographic data and to other information concerning processes and properties related to geographic location. When applied to hydrologic systems, nontopographic information can include description of soils, land use, ground cover, ground water conditions, as well as man-made systems and their characteristics on or below the land surface. Description of topography is called terrain modeling, and because of the tendency of surface water to flow downhill, the hydrologic importance of terrain modeling is clear. While maps have been the most common historical form of representing topography, the advent of digital maps in GIS provides an alternate method of storing and retrieving this information. The amount of digital data required to accurately describe the topography of even small geographic regions make GIS a memory intensive and computationally intensive system. Even so, there is adequate GIS software available for mainframe, mini-, and microcoputers. The characteristic that differentiates a GIS from general computer mapping or drawing systems is the link to the information data base. Once the data base is

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constructed, correlations between different pieces of information can be examined easily through computer-generated overlay maps. For hydrologic modeling purposes, there is generally an extra step of generating hydrologic parameters that are dependent on data-base information. This hydrology-GIS link is a significant complicating factor, because it involves complex empirical or physics-based relations.

Hydrologic applications of GIS's have ranged from synthesis and characterization of hydrologic tendencies to prediction of response to hydrologic events. While the underlying assumption of any GIS application is that the data base of information is available, the acquisition and compilation of the information is hardly a trivial exercise. Often, appropriate data is only available in map form, so that even with modern digitizing hardware and software the process is labor intensive. The payoff comes from the multiple ways in which the data can be used once it is made digitally accessible in a GIS. Thus, it is clear that the potential value of application of GIS to hydrologic modeling and assessment justifies the continued study of this technology. It is less clear however to what degree a GIS can replace current activities now strongly dependent on engineering judgment. Many of the limitations of present GIS capabilities are more related to limitations of data collection and reduction and current hardware capabilities, than to the software architectures used for GIS data handling. Based on current progress in these areas, the optimism of those involved in development of hydrologic applications of GIS appears justified.

GIS Data Types

Topographic Data

One of the capabilities of a GIS most important to hydrologic applications is the description of the topography of a region. Techniques used in the computer description of topography are called digital elevation models (DEM's). Some spatial information is not directly described by elevation, and can be described as topologic data. Topologic data define how the various pieces of the region are connected. Topology can be described as the spatial distribution of terrain attributes. DEM and GIS representations of topologic data are part of the general grouping of digital terrain models (DTM's). An example of hydrologic topology is the collection of lines describing a stream network. Another is the collection of points delineating subregions of a watershed. Both forms of information are related to topography, but may be defined in a topological sense based on the topographic portion of the GIS data base.

Topologic Data

While topographic data fit within the general classification of topologic data, there are significant hydrologic attributes not related to land surface elevation. The more obvious of these are catchment areas, flow lengths, land slope, surface roughness, soil types, and land cover. These attributes help to describe the ability of a region to store and transmit water. Djokic and Maidment (1991) have applied a GIS in conjunction with an expert system to urban drainage, and a significant aspect of the study is the handling of the effects of man-made modifications to terrain. Topographic data for an urban drainage network relate to the direction of movement of water, and the hydrologic attributes relate to the mode of transmission.

Some topologic attributes are tied to the concept of a watershed unit.

The most basic of these is the description of the watershed boundary. Given a drainage point, the topography alone can be used to define those areas that should drain to the point. Average slope and drainage path networks are related, topographically derived, topologic attributes. Speight (1980) gives a more complete list of topographically derived attributes. These attributes are useful in determining watershed attributes such as time of concentration, flow potential energies, and flow attenuation. The sorting and manipulation capabilities of a GIS are well suited to extracting such attributes. The following sections describe several common approaches that have been applied to terrain modeling for hydrologic applications.

GIS Data Handling Approaches

Raster or Grid-Based Data

The first applications of GIS in hydrologic modeling utilized grid cell or raster storage of information (Pentland and Cuthbert 1971). Fig. 1 is a representation of this approach to grid data representation. The grid is made up of regularly spaced lines, and the enclosed area of each rectangle is described in terms of its center coordinates. If the terrain is thought of as a visual image with the dots having various colors and intensities similar to a computer video screen, the use of the term *raster image* used for grid data as well as computer screen images is easily understood. The use of raster representation of terrain is a logical result of the large data base of DEM data available through the U.S. Geologic Survey and the National Cartographic Information Center. An example of a widely used raster-based GIS is the geographic resource analysis support system (GRASS) of the U.S. Army Corps of Engineers ("Geographic" 1991). Some GRASS applications have been made to watershed analysis (Hastings 1990).

It is important to note that there may be different grid scales for different attributes of the terrain, although following the scale of the available data is the obvious first choice. For attributes that are largely homogeneous, the use of the rigid resolution necessary for a DEM would require the storage of large amounts of redundant data. The reduction in data storage from the use of several grid scales comes at the cost of the complexity of translation between the scales to relate the data. Furthermore, as noted by Moore et al. (1991), the grid resolution necessary to resolve the elevation of the most coarse terrain of a region dictates the scale. Nearby smooth terrain will have unnecessary detail in its description.

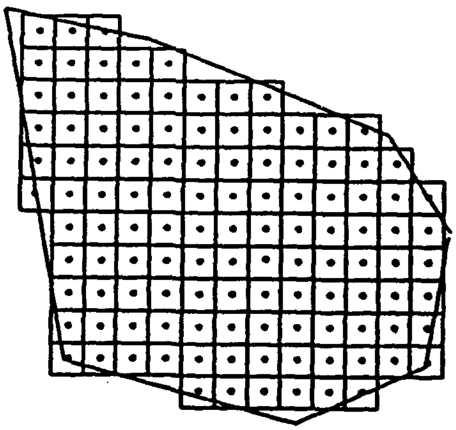

FIG. 1. Grid Representation of Topography

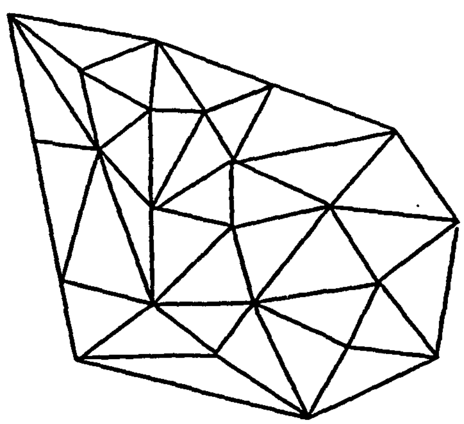

FIG. 2. TIN Representation of Topography

An inherent problem in hydrologic modeling with grid DEM data is the production of nonphysical depressions due to noise in the elevation data affecting interpolation schemes used to describe variation in elevation between raster points. The result is an unwanted termination of drainage paths in pits. The problem is particularly acute for relatively flat areas. O'Callaghan and Mark (1984) and Jenson (1991) have demonstrated techniques for locating and removing depressions in gridded DEM data. The situation is complicated however by the existence of naturally pitted topography, sometimes called pothole regions. The methods are sufficiently flexible to allow accurate flow path delineation even with filling of real depressions.

Triangular Irregular Networks

An alternate approach to producing DEM's relies upon determination of significant peaks and valley points into a collection of irregularly spaced points connected by lines as shown in Fig. 2. The lines produce a patchwork of triangles known as a triangular irregular network (TIN). Most typically the triangles are treated as planar facets, but smoother interpolation is possible. The problems of depressions and interrupted drainage paths are partly avoided with a TIN as the path of water movement follows the slope of a plane or flows down the edge between two triangles. Due to the fact that triangle networks from points are nonunique, several algorithms have been developed to produce them from sets of points. The most widely used is known as Delauney triangulation (Lee and Schacter 1980) based on a principle of maximizing the minimum angle of all triangles produced by connector lines to nearest neighbor points. Christensen (1987) developed methods to circumvent poor representation of nearly equivalent elevations for the method, making accurate elevation representation more reliable. One of the main TIN systems available commercially is *ARC/INFO* (1991).

As with raster methods, scales of representation for attributes other than elevation need not be the same as the TIN. In addition, the triangle-based representation can be a subset of a more general polygonal description of attribute regions. The areal design and planning tool (ADAPT) was one of the first TIN applications (Grayman et al. 1975) of GIS to a hydrologic problem. While the application was aimed at predicting water quality and sewer flows, the extensions to more purely hydrologic problems (Jett et al. 1979) were reported shortly thereafter. One of the most useful characteristics of a TIN for hydrologic system is the ability to define streams in terms of triangle boundary segments. This allows a more continuous description of stream paths and networks in conjunction with the topography. By comparison, grid data tend to produce zig-zag meandering paths for streams on upslope portions of a watershed.

Vector- or Contour-Based Line Networks

The third major form of representing topography is contour line mapping. The contours can be represented digitally as a set of point-to-point paths (vectors) of a common elevation as shown in Fig. 3. When an entire map is stored in this digital form it is called a digital line graph (DLG). Most commercially available GIS's have the ability to transform between DLG's, grid DEM's, and TIN DEM's, but as noted by Moore et al. (1991) contour-based methods require an order of magnitude more data storage, so that the transformation is typically from DLG's to the other forms. Moore et al. (1988) have developed hydrologic applications using contour lines along with an orthogonal set of intersecting lines describing steepest descent to

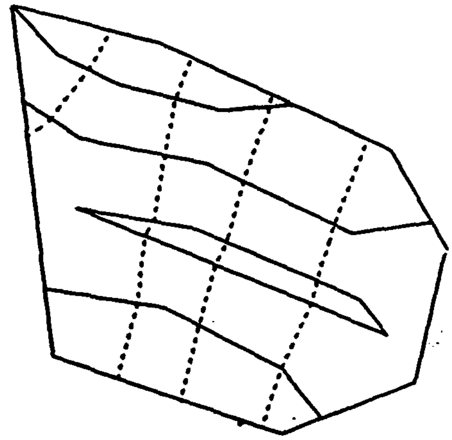

FIG. 3. Contour-Based Representation of Topography

divide the mapped region into quadrilaterals. The chief advantage of the approach is that an important hydrologic attribute (steepest descent path) is inherent in the resulting data structure.

Use of Remotely Sensed Data

Data for a GIS can be collected from ground surveys, digitizing existing maps, digitally recorded aerial photography, satellite imaging data, or combinations of these. A problem of the scale of accuracy arises when these data are used in combination, so there is a disincentive to mix them. Aerial photography is the oldest of techniques for determining topology from a remote location. This has the ability to produce DEM data accurate to 0.03% of the altitude of photography (Kelly et al. 1977). Satellites have been used for several decades for remote sensing, and the potential for applications in hydrology were quickly recognized ("An Assessment" 1974). Brooner et al. (1987) have described the many hydrologically significant parameters that can be obtained through remote sensing, including land cover, vegetation properties, thermal and moisture indices, snow cover, and imperviousness. Most of these are obtained through satellite imagery. However, not all information from satellites is imagery. Satellites are often used for communication of hydrologic data from land-based sensors to analysis centers. This data can be entered into a GIS with little processing, while imagery requires considerably more processing.

In a series of studies aimed at evaluating the role of remote sensing in hydrologic modeling, NASA (Peck et al. 1983; Johnson et al. 1982; Peck et al. 1981) evaluated the limitations remotely sensed data places on hydrologic models and vice versa. The emphasis was placed on attributes evaluated from satellite data as areal averages. Such attribute data is typically used in models that describe hydrologic response in terms of watershed units that can be significantly larger than the resolution of the satellite data that can be as small as 10 m. These models have been categorized as lumped parameter models. Kovas (1991) notes the importance of additional data collection, especially when a GIS is used for urban hydrology. The technique of enhancing the GIS terrain description by use of kinematic global positional system (GPS) units is described. GPS allows accurate location of hydraulic control points such as curbs and valves, and can greatly improve the ability of the GIS and hydrologic model in prediction of flow paths in an urban setting.

Brooner et al. (1987) note that laser and gamma-ray technology can also be used to remotely acquire information useful to hydrologic modeling. These techniques are useful for water body bed delineation and for surface moisture levels, respectively. Radar, a tool long used for meteorologic purposes, now shows promise for real-time sensing of the spatial and temporal distribution of precipitation. This capability will be especially useful for flood forecasting. The primary hydrologic use would be in tracking rainfall, however since GIS's were not originally envisioned as a time series data-base tool, they are not optimally suited for handling time varying data. This is an area where further development could enhance GIS utility.

Hydrologic Modeling Approaches in GIS Context

Rainfall-Runoff Models

Prediction of surface runoff is one of the most useful hydrologic capabilities of a GIS system. The prediction may be used to assess or predict aspects of flooding, aid in reservoir operation, or be used to aid in the prediction of the transport of water-borne contaminants. The types of models that have been applied with a GIS will be classified as lumped parameter, physics based (implying full spatial distribution and modeling for runoff related attributes), or some combination of the two.

Lumped Parameter Models

The basic unit of a lumped parameter model is normally taken to be a subbasin of the total watershed being considered. Each subbasin is taken as a hydrologic response unit, so that all attributes must be averaged or consolidated into unit-level parameters. The distinction between lumped parameter and distributed models is not as clear as might be desired, because the subbasin may be taken to be arbitrarily small. Furthermore, the point-by-point descriptions of processes such as infiltration, interflow, and overland flow are sometimes modeled as separately contributing processes in a subbasin. In this way, processes in complex terrain are modeled physically as simple plane (or square bin) processes occurring separately from each other. The U.S. Army Corps of Engineers hydrologic model HEC-1 (*HEC-1 Flood* 1990) is an example of a model classified here as a lumped parameter model, but can effectively operate as a distributed model through small subbasins and/or kinematic wave routing options. Several authors have cited GIS applications of HEC-1. Berich (1985) describes a raster-based system that is suited for application of satellite terrain data and has been tested on two lumped parameter models, namely HEC-1 and the Soil Conservation Service's TR-20 model ("An assessment" 1965). Both applications utilize SCS runoff curve number estimation from raster data describing land use and soil type. Schmidt et al. (1987) and Warwick et al. (1991) also describe GIS application of HEC-1. The latter describes integration of HEC-1 with the GIS, but significant user interaction is still required. Cline et al. (1989) describe the application of the microcomputer graphics software Auto-CAD and HEC-1 in what they call a watershed information system (WIS). The WIS performs many of the same functions as a standard GIS, although additional computer code was generated to extract model parameters and prepare HEC-1 input files.

Ragan and White (1985) and Fellows (1985) describe application of a grid cell data system in conjunction with the SCS TR-55 lumped parameter model. The system includes watershed delineation, and the latter was developed to be able to easily translate satellite data to the parameters necessary for the model. The emphasis of Ragan and White is on demonstration of a personal computer application of a GIS hydrology system. The concept of region growing is applied to extact watershed boundaries by examining drainage paths over grid elevation data.

Physics Based Models

The lumped parameter model applications cited use empirical approaches to describe the runoff phenomenon. In comparison, a physics-based model uses some form of balance equation defined at all points to model runoff flows. The most common approach is the application of the Saint Venant equations of shallow water flow, which conserve water momentum and volume. When interflow is considered, Darcy's law of porous medium flow is used. When applied to a two-dimensional surface, these balance equations are second order partial differential equations in time and space which must be solved by approximation methods. The solution approach is generally dictated by the form in which the data is stored. For example, grid data lends itself to application of finite difference methods, while TIN data is better suited to finite element methods.

Although not applied in a true GIS system, Li et al. (1977) describe the application of the kinematic wave approximation for shallow water equations in a finite element solution to overland flow routing. The segmentation of the terrain data and the input information necessary to predict local runoff rates pointed toward the utility of applying a GIS. Vieux (1991) has applied a finite element solution of the kinematic wave equation in conjunction with a TIN, but the elements are much larger than the TIN triangles. Vieux describes the difference between distributed and lumped modeling in terms of the scales of the physical process and modeling. When the model uses an element smaller than the size of the scale of the physical process, it is described as distributed, and when the scale of the model is of the scale of the process (the whole watershed), it is called a lumped model. This description highlights the subjectivity of such classifications, because it might rightfully be claimed that the scale of the process of overland flow is even smaller than the TIN triangles.

Silfer et al. (1987a, 1987b) have used a TIN in the finite difference solution of the kinematic wave and Darcy flow equations in their TINFLOW system. The TIN facets are analyzed in a preprocessing algorithm to prepare a flow network of one-dimensional (1-D) flow pipes, and then the 1-D forms of the governing equations are solved simultaneously for the separate segments. In a similar approach, Hong and Eli (1985) describe the framework of a model to be applied to a fully 2-D TIN, but only test it on a cascade of 1-D planes. Eli (1990) expands on the concept and applies the cellular automata computational concept to predefine drainage paths. The iterative technique is based on nearest neighbor interactions, which orders drainage paths to take advantage of massively parallel computational algorithms.

The 1-D flow network discretization approaches just described can be applied to kinematic wave routing over connected planes, because the assumptions inherent to the kinematic wave equations require that flow always be in the direction of the principal slope. This was described initially by Onstad and Brakensiek (1968). Moore et al. (1991) apply this concept with a contour-based vector DEM to predict overland and interflow runoff flow components. The computational element is a quadrilateral bounded by neighboring contour lines on two opposite sides, and closed by flow stream-lines on the other two sides. An alternate method based on minimum distance between adjacent contour lines is used for defining the quadrilateral sides for ridge areas. The alternate methods are necessary due to the errors introduced by treating streamline segments as straight lines.

Hybrid Models

Some of the reported models do not fit conveniently in classifications of lumped parameter or physics based. For example, Johnson (1989) describes a model that allows choice of lumped parameter or distributed modeling. Djokic and Maidment (1991) use a TIN system to describe urban drainage in terms of tube networks. The overland flows are approximated in terms of fixed transit times (times of concentration). This approach allows convenient flow linking to storm sewers and gutters specific to urban hydrology.

The CEQUEAU of Charbonneau et al. (1975) solves balance equations on a subbasin scale to predict runoff. Terrain data is stored in a grid format and is used to develop input parameters for the physics/empirical model. O'Loughlin (1986) describes a contour-based system that uses surface saturation tendencies to predict runoff. Both of these two previous models include descriptions based on physics, but they do not use fully 2-D distributed balance equation description.

General Indices

In some cases complete rainfall/runoff response need not be described to provide the necessary hydrologic engineering information. General indices of the tendency to produce runoff may be sufficient. Decision making can be based on simple maps of terrain properties. It is in these applications that GIS methods can be most quickly and efficiently applied. Further, the map data produced can be saved for future use in actual rainfall runoff prediction if they are stored in a form appropriate to the model to be used.

Imperviousness

A recent trend toward storm sewer fee assessment has led to the need for an objective measure of relative contributions to flows from different urban properties. Allen (1991) and Williams and Rosengren (1991) describe the application of GIS methods as a basis for fee assessment. The main criterion is the percent of impervious area of the property. They made no actual runoff computations.

Natural Land Cover

When remotely sensed data is brought into a GIS, information about vegetation and other natural cover can be extracted by examining the spectral print of the region. Duchon et al. (1990) use this approach along with temperature data to prepare input for a monthly water budget model. They found that subdivision by land cover type produced better model results than those subdivided according to subbasins. It is important to note that the land cover maps produced for this study could also be used for single event runoff studies. Such maps are also useful in community development and planning. Kilgore and Katz (1991) note however, that differences as high as 30% were observed between land cover-derived and subbasin-derived SCS curve numbers from distributed data.

Watershed Delineation and Stream Networks

The information gained in the process of determining the path of runoff and the limits of a watershed is useful in both hydrologic and water quality terms. Several systems have been developed for these purposes, with the end result of the GIS manipulations being watershed boundaries and stream paths. As described previously, Fellows (1985) describes a raster-based process called region growing used to extract water path data. Jones et al. (1990) use a TIN system and steepest descent and ascent to delineate drainage boundaries, and determine flow paths and stream networks. The TIN is particularly suited to steepest descent/ascent because of the uniform slope along each triangle facet.

A raster DEM is used by Bevin et al. (1991) to extract hillslope flow paths using a flow path index. The index is based on the upflow area (contributing area) and local slope. The authors point out that this index approach has inherent assumptions of quasi-steady conditions and ground water tables roughly mirroring the topography. Tarboton et al. (1991) apply a contributing area accumulation method to grid data to define channels according to a threshold number of contributing grid cells. The data manipulation is greater than with TIN methods, and depression filling was also required. It should be realized however, that there is a significant data base of grid data, and that TIN's are often constructed originally from gridded data. This means that often significant data manipulation is necessary before the TIN approaches may be applied. TIN's can also be readily developed from land survey data.

End Uses of GIS Hydrology

The prediction of runoff history may be only one component of prediction of the results of watershed runoff. The runoff can cause erosion, flood damage, and transport contaminants. Often the accuracy of the runoff model is dictated by the accuracy required by a model secondary to the hydrologic model. The resolution of the DEM also can be determined by necessary accuracy of the end model. The following published studies are examples of end uses of GIS hydrologic predictions. The applications cited are indicative of the range of possibilities, but the list is by no means exhaustive.

Floodplain Management and Flood Forecasting

A grid cell data bank was used by Davis (1978) to assess flood damage using HEC-1 and the profile program HEC-2. Polygon data was used, but it was converted to grid cell format before application. Water quality and erosion modeling were also considered in the framework of a flood event. Murphy and Hoegberg (1991) also use a GIS for flood damage assessment, but the emphasis is on continuing management. Thus, single event simulation is less important and general indices are of greater use. DLG data was used because it was the most accurate available data bank.

A somewhat different form of flood flow prediction is used in the process of flood forecasting. In forecasting, the emphasis is on real-time prediction of flood conditions. Tao and Kouwen (1989) describe a grid-based technique of flood forecasting which allows a choice of distributed modeling or lumped parameter modeling. The grid size is rather large (10×10 km), but a satellite image data base is averaged over the grid scale, which accomplishes a preliminary form of parameter lumping. VanBlargan and Schaake (1987) use the grid data and a kinematic wave model to predict flood events. A finite difference approach is used to solve the kinematic wave equations for both overland flow and channel routing.

Erosion Prediction/Control

Using a TIN and the kinematic wave equation, Eli and several investigators (Eli et al. 1980; Eli and Paulin 1983; Eli 1981) applied GIS methodology to surface mined lands. The universal soil loss equation (USLE) was used to predict erosion. The USLE does not require runoff information, only information concerning soil, land cover, rainfall intensity, and topographic properties. Therefore the USLE predicts erosion potential, but the kinematic wave and erosion predictions are used together to determine suspended sediment loads. In this way, it is clear that erosion prediction and water quality prediction are linked. It is indicative of the simplicity of determination of parameters for the USLE from GIS data that there are few citations of its use in open literature. It should be realized that erosion potential prediction is a practical and widely applied GIS operation. Gupta and Solomon (1977) do not use the USLE, but they employ a combination of empirical and physics based modeling in their river sediment discharge model. The grid cell system is shown to be superior to simpler techniques when ungaged watersheds are considered.

Water Quality Prediction/Control

Air and water are the primary carriers for contaminants in the terrestrial environment. Any form of moving water is a potential transporter of pollution. The movement is potentially good in that it can disperse contaminants; but no matter why information is needed about contaminant movement, knowledge of the magnitude and temporal distribution of flow is necessary for accurate prediction of the movement. The prediction of movement of distributed surface contaminants known as nonpoint pollution is one of the applications most amenable to GIS's, and several researchers have reported their development. DeBarry (1991) uses DLG topographic data and polygonal description of soil and ground cover information in a pollution assessment system. General estimates of potential for pollutant export from each watershed were computed rather than time varying predictions, because the system was developed as a planning tool and single event estimates were not as important as long-term trends. Lee and Terstriep (1991) developed a GIS interface for the agricultural nonpoint source pollution model (AGNPS) (Young et al. 1987). AGNPS is a grid cell, single event model that predicts erosion, suspended sediment, and other quality parameters. Young et al. (1987) report relatively good flow prediction agreement and poor quality agreement in their validation run. They highlight the need for calibration of their model. Vieux (1991) has developed a TIN nonpoint modeling system using a finite element solution of the kinematic wave equation. An interface to AGNPS using lumped parameter hydrologic modeling is described, but it is not clear whether it was applied to the output of the finite element model.

Quality predictions for urban hydrology have become of increasing importance as stormwater quality regulations have toughened. Cowden (1991) describes a two part approach to a stormwater/wastewater quality management system. The input for the quality model is prepared by the GIS, downloaded to a microcomputer, and then the model predictions are made. The results from the quality model are then uploaded back to the system in GIS format. Kruzich (1991) outlines the use of a GIS in urban quality modeling, but also cites applications in groundwater contamination source delineation and discharge permit tracking.

Drainage Utility Implementations

Drainage utility applications were discussed earlier (Allen 1991; Williams and Rosengren 1991) in describing the general index of percent imperviousness. The data base required is not as extensive as other applications, because no runoff modeling is performed. More detail might be justified if the systems could be used for other purposes such as urban water quality management. Then part of the cost of constructing the data base could be defrayed.

HEC's Role in GIS/Hydrology Development

Grid Cell Data Banks

The Hydrologic Engineering Center (HEC) has played an important role in the development of computer methods in hydrology. Standard application of HEC-developed software can sometimes require extensive manipulation of map data to prepare input for the programs. Some of the earliest work by HEC related to GIS hydrology involved development of a systematic methodology for automating the data preparation process (*Guide Manual* 1978). The raster-based organization chosen was called a grid cell data bank. Techniques for use of satellite data, for conversion of polygon data to grid format, and for use of commercially available software to manipulate and convert the data were discussed. Maintenance and support requirements for the data base were also described.

The grid cell data bank approach was used in the development of software for the extraction of hydrologic parameters called HYDPAR ("Application of" 1983). An application toward the prediction of runoff for the Pennypack Creek watershed ("Pennypack Creek" 1978) was used to demonstrate capabilities. Watershed and subbasin delineation was not automated, but unit hydrograph information was derived using GIS techniques. Display capabilities common to GIS platforms were also included.

HEC-SAM

Another offshoot of the grid cell data bank methodology was HEC spatial analysis methodology (HEC-SAM) ("Flood Mitigation" 1980). The new capabilities included use of satellite imagery and links to more extensive GIS data banks. The end products still used a grid cell approach. HEC-SAM was developed as a forecasting and planning tool, and has been applied in a number of U.S. Army Corps of Engineers studies ("Application of" 1986).

Remotely Sensed Data Manipulation

At about the same time HEC was developing grid cell data bank methods, work was also being performed to assess the usefulness and appropriate role of satellite imagery in GIS hydrology. An initial assessment ("An Assessment" 1974) was aimed at application with HEC computer programs. A later study focused on the more generic application of determination of land use classifications from satellite data ("Determination of" 1979), but verification was still performed with HEC-1. More recently, HEC commissioned a report from the Earth Satellite Corp. (Brooner et al. 1987) assessing present and future uses of remotely sensed data in hydrologic modeling. The report detailed how new technologies could be applied in the determination of land cover, snow cover, precipitation estimates, and surface water distribution.

HEC/ADAPT

HEC contracted with the University of California at Davis ("Application of" 1991) to investigate the application of a TIN GIS link with HEC-1. In previous work with W. E. Gates and Assoc. (*Contract Report* 1982), HEC had obtained the ADAPT TIN software system for use with HEC-1. An interface program linking HEC-1 with ADAPT (dubbed HECAD) was developed by Walter Grayman as a part of that W. E. Gates contract. The TIN triangles were manually determined, but in principle could have been extracted from a DEM data base if that were available. HECAD prepares input to HEC-1 by calculating uniform loss functions from the distributed values of soil type and land cover, as well as accounting for overland flow and channel velocities in terms of roughness and slope. The model was applied to both an urban and a nonurban basin, and provided accurate predictions. The approach was not compared to previous grid cell data bank predictions. It does however provide an alternate technique to previous HEC grid-based approaches.

CONCLUSIONS AND RECOMMENDATIONS

From the previous discussions it is clear that GIS's have been effectively used in a variety of hydrologic applications. However the cost of implementing a GIS can be significant, especially when the cost of data collection and manipulation is considered. Thus, it is best when the data base can be shared for several related purposes. For example, a GIS data base assembled for flood forecasting could also be of use in nonpoint pollution monitoring. Unfortunately, the organizations interested in these two activities are distinctly different, and should they decide to invest in GIS technology, it is not likely that they would wish to have a data base not custom oriented to their application. When one considers the many potential end applications of a GIS, from hydrologic predictions to regional resource management, some sort of interorganizational effort will be necessary to share the costs and benefits of a GIS.

Part of the problem in acceptance of GIS methodology in hydrology for other than research purposes is tied to the customized nature of many of the applications. Another more troubling reason for lack of acceptance is the lack of clear evidence of the superiority of GIS results to more traditional methods. To the hydrologic engineer, there is little difference in the tedium of hand measurements from U.S.G.S. maps and digitizing the same information. Computer manipulation of remotely sensed data removes the tedium aspect, but the inaccuracies of interpreting spectral data again leads to the question of superiority to standard manual data entry methods. The question can only be resolved through a broad based validation study. In the U.S. such studies have only been successful when undertaken by a federal agency. A study of such a large scope will not likely be undertaken until GIS hydrology becomes more widely used in the field.

There is also a lack of consensus with regard to the various GIS and hydrologic models applied. Grid, polygon, and vector representations have been shown to each have unique positive aspects. Physics based hydrologic models have not been shown to be intrinsically better than lumped parameter model for runoff prediction. The improved detail of so called distributed models leads to its own problems. Even though GIS's can accurately resolve spatial variation in terrain attributes, there is question as to the validity of applying hydrologic models at that scale. Woodward and Cronshey (1990) note this fact in discussing the grid-based curve number determination methods of White (1989). They note that SCS curve numbers were developed from evaluation of small, relatively uniform attribute watersheds, and that uniform rainfall was assumed. Fully distributing the conditions creates conditions where movement of water from one part of the watershed to another can significantly affect the runoff distribution. Furthermore interflow effects, not important when parameters are lumped and rainfall is uniform, can become important to spatial variability when they are not.

Physics-based models are also subject to the same problems of spatial resolution as the lumped models. Rainfall, infiltration and runoff detail in a model should, in the optimum, reflect the resolution provided by the GIS. If surface and subsurface flows are modeled, then their interdependence can also be important. Freeze (1972) and Smith and Hebbert (1983) have discussed the physics of these processes, and when considered in a GIS model system, their addition complicates the analysis of the model, however the added complexity appears warranted if other processes are resolved in the same spatial detail. One of the most important of these other processes is the spatial distribution of rainfall. For some regions, an assumption of rainfall uniformly distributed in time and space is a very crude approximation. Infiltration is a mechanism for spatial redistribution of rainfall, and so when it is considered, realistic spatial resolution of rainfall should also be attempted. Better spatial and temporal definition of rainfall will soon be available via the new NEXRAD radar systems.

The future of GIS applications for hydrologic modeling is not obviously evident, but it is clear that there is considerable interest in exploring the limits of emerging computer technology. While current GIS applications in hydrology are primarily work station based, future technology may bring GIS to the desktop. With less limitation from computing power, the focus of future advancements may be improved data collection, expanded data bases, and advances in numerical modeling approaches. Education will also play a key role in the future success of the methodology. Education will have to emphasize not only the mechanisms of GIS usage, but also the application of GIS to hydrologic analysis. Recent graduates in science and engineering have greater computer literacy than past generations. Whether their numbers and training will be sufficient to allow general use of GIS in hydrology is yet to be determined. GIS will have "arrived" in hydrology when it is viewed as merely another analysis tool.

Appendix. References

Allen, D. W. (1991). "Euliss uses its GIS for a drainage utility." *Geo. Info. Syst.*, 1(5), 22–24.

"An assessment of remote sensing applications in hydrologic engineering." (1974). *Res. Note No. 4*, Hydrologic Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

ARC/INFO product information. (1991). Environ. Systems Res. Inst., Redlands, Calif.

"Application of a geographic information system to rainfall-runoff modeling." (1991). *Res. Document No. 36*, Hydro. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

"Application of spatial data management techniques to HEC-1 rainfall-runoff studies." (1983). *Training Document 19*, Hydro. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

"Application of spatial-data management techniques in corps planning." (1986). *Technical Paper No. 115*, Hydro. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

Berich, R. H. (1985). "A Micro-computer GIS for water resources planning." *Proc., Comp. Applic. in Water Resour.*, ASCE, 58–67.

Bevin, P. Q. K., Chevallier, P., and Planchon, O. (1991). "The prediction of flow paths for distributed hydrological modelling using digital terrain models." *Hydro. Process.*, 5(1), 59–79.

Brooner, W. G., Merritt, E. S., Place, M., Ragan, R. M., Wiesnet, D., and Deutch, M. (1987). "Remote sensing technologies and spatial data applications relevant to HEC programs and mission." *Final Report Contract No. DACWO5-87-C-0012*, U.S. Army Corps of Engrs., Davis, Calif.

Charbonneau, R., Fortin, J. P., and Morin, G. (1975). *The CEQUEAU model: Descriptions and examples of its use in problems related to water resources management.* Institut Nationale de la Recherche Scientifique, University of Québec, Québec, Canada.

Christensen, A. H. J. (1987). "Fitting a triangulation of contour lines." *Auto-Carto 8, 8th Int. Symp. on Comp.-Assisted Cartog.*, American Society of Photogrammetry and Remote Sensing, 57–67.

Computer Program for Project Formulation Hydrology. (1965). *Technical Release No. 20*, U.S. Dept. of Agric., Soil Conservation Service, Washington, D.C.

Contract report on Use of ADAPT with HEC-1. (1982). Hydrologic Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

Cline, T. J., Molinas, A., and Julien, P. Y. (1989). "An Auto-CAD-based watershed information system for the hydrologic model HEC-1." *Water Resour. Bull.*, 25(3), 641–652.

Cowden, R. W. (1991). "Stormwater/wastewater management: How an application can drive a GIS." *Water Resour.: Plng., Mgmt., and Urban Water Resour., Proc., 18th Conf.*, ASCE, New York, N.Y., 913–917.

Davis, D. W. (1978). "Comprehensive flood plain studies using spatial data management techniques." *Water Resour. Bull.*, 14(3), 587–604.

DeBarry, P. A. (1991). "G.I.S. applications in nonpoint source pollution." *Hydr. Engrg., Proc., 1991 Nat. Conf.*, ASCE, New York, N.Y., 882–887.

"Determination of land use from LANDSAT imagery: applications to hydrologic modeling." (1979). *Res. Document No. 7*, Hydr. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

Djokic, D., and Maidment, D. R. (1991). "Terrain analysis for urban stormwater modelling." *Hydr. Process.*, 5(1), 115–124.

Duchon, C. E., and Nicks, A. D. (1990). "Application of satellite remote sensing to hydrologic modeling." *EOS, Trans. Am., Geophys. Union*, 71(43), 1348.

Eli, R. N. (1981). "Small watershed modeling using DTM." *Water Forum '81*, ASCE, 2 (Aug.), 1233–1240.

Eli, R. N. (1990). "A cellular automation drainage processor for large scale spatially distributed hydrologic models." *EOS. Trans., Am. Geophys. Union*, 71(43), 1348.

Eli, R. N., Palmer, B. L., and Hamrio, R. L. (1980). "Digital terrain modeling applications in surface mining hydrology." *Symp. Surface Mining Hydro., Sedimentology, and Reclamation*, Univ. of Kentucky, 445–453.

Eli, R. N., and Paulin, M. J. (1983). "Runoff and erosion predictions using a surface mine digital terrain model." *Symp. Surface Mining Hydro., Sedimentology, and Reclamation*, University of Kentucky, 201–210.

Fellows, J. D. (1985). "A Geographic information system for regional hydrologic modeling." *Hydrologic Research Series Report*, Remote Systems Sensing Lab., Univ. of Maryland, College Park, Md.

"Flood mitigation planning using HEC-SAM. (1980). *Technical Paper No. 73*, Hydro. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

Freeze, R. A. (1972). "Role of subsurface flow in generating surface runoff: 2. Upstream source areas." *Water Resour. Res.*, 8(5), 1272–1283.

"Geographic Resource Analysis Support System." (1991). *Version 4.0*, Constr. Engrg. Res. Lab., Champaign, Ill.

Grayman, W. M., Males, R. M., Gates, W. E., and Hadder, A. W. (1975). "Land-based modeling system for water quality management studies." *J. Hydr. Div.*, ASCE, 101(5), 567–580.

Guide manual for the creation of grid cell data banks. (1978). Hydro. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

Gupta, S. K., and Solomon, S. I. (1977). "Distributed numerical model for estimating runoff and sediment discharge of ungaged rivers." *Water Resour. Res.*, 13(3), 613–636.

Hastings, D. (1990). "GRASS for hydrologic modeling." *GRASSclippings, GRASS Newsletter,* U.S. Army Corps of Engrs., Civ. Engrg. Res. Lab., Champaign, Ill., 4(2), 1–6.

HEC-1 flood hydrograph package, user's manual. (1990). Hydro. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.

Hong, H. M., and Eli, R. N. (1985). "Accumulation of streamflow in complex topography." *Comp. Applic. in Water Resour., Proc., ASCE Specialty Conf.*, ASCE, New York, N.Y., 196–205.

Jenson, S. K. (1991). "Applications of hydrologic information automatically tracted from digital elevation models." *Hydro. Process.*, 5(1), 31–44.

Jett, S. C., Weeks, A. D., and Grayman, W. M. (1979). "Geographic informati systems in hydrologic modeling." *Proc., Hydro. Transport Symp.*, American Society of Agricultural Engineers, St. Joseph, Mich., 127–137.

Johnson, L. E. (1989). "A digital map-based hydrologic modeling system." *Photogram. Engrg. and Remote Sens.*, 55(6), 911–917.

Johnson, E. R., Peck, E. L., and Keefer, T. N. (1982). "Combining remotely sensed and other measurements for hydrologic areal averages." *NASA Report NASA-CR-170457*, Goddard Space Flight Ctr., Greenbelt, Md.

Jones, N. L., Wright, S. G., and Maidment, D. R. (1990). "Watershed delineation with triangle-based terrain models." *J. Hydr. Engrg.*, ASCE, 116(10), 1232–1251.

Kelly, R. E., McConnel, P. R. H., and Mildenberger, S. J. (1977). "The Gestalt photomapping system." *Photogram. Engrg. and Remote Sens.*, 43(11), 1407–1417.

Kilgore, R. T., and Zatz, M. N. (1991). "Is GIS better or different." *Water Resour.: Plng. Mgmt., and Urban Water Resour., Proc., 18th Conf.*, ASCE, New York, N.Y., 893–897.

Kovas, J. E. (1991). "Field data-gathering: Critical first step for a GIS." *Water Resour.: Plng., Mgmt., and Urban Water Resour., Proc., 18th Conf.*, ASCE, New York, N.Y., 898–907.

Kruzich, R. (1991). "Using a GIS to manage water resources in Texas." *Water Resour.: Plng., Mgmt., and Urban Water Resour., Proc., 18th Conf.*, ASCE, New York, N.Y., 908–912.

Lee, D. T., and Schacter, B. J. (1980). "Two algorithms for constructing a Delauney triangulation." *Int. J. Comp. Info. Sci.*, ASCE, New York, N.Y., 9(3), 219–242.

Lee, M. T., and Terstriep, M. L. (1991). "Applications of GIS for water quality modeling in agricultural and urban watershed." *Hydr. Engrg., Proc., 1991 Nat. Conf.*, ASCE, New York, N.Y., 961–965.

Li, E. A., Shanholtz, V. O., Contractor, D. N., and Carr, J. C. (1977). "Generating rainfall excess based on readily determinable soil and landscape characteristics." *Trans.*, American Society of Agricultural Engineers, 20(6), 1070–1078.

Moore, I. D., Grayson, R. B., and Burch, G. J. (1988). "A contour-based topographic model for hydrological and ecological applications." *Earth Surface Processes and Landforms*, 13(4), 305–320.

Moore, I. D., Grayson, R. B., and Ladson, A. R. (1991). "Digital terrain modeling: A review of hydrological, geomorphological, and biological applications." *Hydro. Process.*, 5(1), 3–30.

Murphy, J., and Hoegberg, L. (1991). "Leading edge or bleeding edge: Management skills make floodplain project go smoothly." *Geo. Info. Syst.*, 1(1), 30–35.

O'Callaghan, J. F., and Mark, D. M. (1984). "The extraction of drainage data from digital elevation data." *Comp. Vision, Graphics, and Image Process.*, 28(3), 323–344.

O'Loughlin, E. M. (1986). "Prediction of surface saturation zones in natural catchments by topographic analysis." *Water Resour. Res.*, 22(5), 794–804.

Onstad, C. A., and Brakensiek, D. L. (1968). "Watershed simulation by stream path analogy." *Water Resour. Res.*, 4(5), 965–971.

Peck, E. L., McQuivey, R., Keefer, T. N., Johnson, E. R., and Erekson, J. (1981). "Review of hydrologic models for evaluating use of remote sensing capabilities." *NASA Report NASA-CR-166674*, Goddard Space Flight Ctr., Greenbelt, Md.
Peck, E. L., Johnson, E. R., and Keefer, T. N. (1983). "Creating a bridge between remote sensing and hydrologic models." *NASA Report-CR-170517*, Goddard Space Flight Ctr., Greenbelt, Md.
"Pennypack Creek XFPI hydrology, Philadelphia, Montgomery and Bucks CO, PA." (1978). *Special Projects Memo No. 78-7*, Hydr. Engrg. Ctr., U.S. Army Corps of Engrs., Davis, Calif.
Pentland, R. L., and Cuthbert, D. L. (1971). "Operational hydrology for ungaged streams by the grid square technique." *Water Resour. Res.*, 7(2), 283–291.
Ragan, R. M., and White, E. J. (1985). "The microcomputer as an intelligent workstation in large scale hydrologic modeling." *Proc., ASCE Conf. Hydr. Hydro. in the Small Computer Age*, ASCE, 908–912.
Schmidt, A. R., Weiss, L. S., and Oberg, K. A. (1987). "Geographic estimation of runoff-model parameters." *Proc., Symp. Engrg. Hydro.*, ASCE, New York, N.Y., 551–554.
Silfer, A. T., Hassett, J. M., and Kinn, G. J. (1987a). "Hydrologic runoff modeling of small watersheds: The TINFLOW model." *Proc., Symp. Engrg. Hydro.*, ASCE, New York, N.Y., 545–550.
Silfer, A. T., Kinn, G. J., and Hasset, J. M. (1987b). "A geographic information system utilizing the triangulated irregular network as a basis for hydrologic modeling." *Auto-Carto 8, Eight Int. Symp. Comp.-Assisted Carto.*, American Society of Photogrammetry and Remote Sensing, 129–136.
Smith, R. E., and Hebbert, R. H. B. (1983). "Mathematical simulation of interdependent surface and subsurface hydrologic processes." *Water Resour. Res.*, 19(4), 987–1001.
Speight, J. G. (1980). "The role of topography in controlling throughflow generation: A discussion." *Earth Surface Process. and Landforms*, 5(2), 187–191.
Tao, T., and Kouwen, N. (1989). "Remote sensing and fully distributed modeling for flood forecasting." *J. Water Resour. Plng. and Mgmt.*, ASCE, 115(6), 809–823.
Tarboton, D. G. (1991). "On the extraction of channel networks from digital elevation data." *Hydro. Process.*, 5(1), 81–100.
VanBlargan, E. J., and Schaake, J. C. (1987). "A flood prediction geographic information system." *Proc., Symp. Engrg. Hydro.*, ASCE, New York, N.Y., 555–560.
Vieux, B. E. (1991). "Geographic information systems and non-point source water quality and quantity modeling." *Hydro. Processes*, 5, 101–113.
Warwick, J. J., Haness, S. J., and Dickey, R. O. (1991). "Integration of an ARC/INFO GIS with HEC-1." *Water Resour.: Plng., Mgmt., and Urban Water Resour., Proc. of the 18th Conf.*, 1029–1033.
White, D. (1989). "Grid-based application of runoff curve numbers." *J. Water Resour. Plng. and Mgmt.*, 114(6), 601–612.
Williams, T., and Rosengren, R. (1991). "Denver's equitable approach to storm sewer assessment." *Geo. Info. Sys.*, 1(2), 20–21.
Woodward, D. E., and Cronshey, R. G. (1990). Discussion of "Grid-based application of runoff curve numbers." by D. White, *J. Water Resour. Plng. and Mgmt.*, ASCE, 116(6), 842.
Young, R. A., Onstad, C. A., Bosch, D. D., and Anderson, W. P. (1987). "AGNPS, agricultural nonpoint source pollution model, A watershed analysis tool." *Conservation Report 35*. U.S. Dept. of Agric., Washington, D.C.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Geographic information systems (GIS) provide a digital representation of watershed characteristics used in hydrologic modeling. This paper summarizes past efforts and current trends in using digital terrain models and GIS to perform hydrologic analyses. Three methods of geographic information storage are discussed: raster or grid, triangulated irregular network, and contour-based line networks. The computational, geographic, and hydrologic aspects of each data-storage method are analyzed. The use of remotely sensed data in GIS and hydrologic modeling is reviewed. Lumped parameter, physics-based, and hybrid approaches to hydrologic modeling are discussed with respect to their geographic data inputs. Finally, several applications areas (e.g., floodplain hydrology, and erosion prediction) for GIS hydrology are described.

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