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DIS and Distributed Watershed Models I

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GIS AND DISTRIBUTED WATERSHED MODELS. I: DATA COVERAGES AND SOURCES

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ABSTRACT: The increasing proliferation of spatial data, geographic information systems (GIS), and models for hydrologic applications provide many new investigation opportunities but also present a number of challenges for the uninitiated water resources practitioner. This two-part paper is intended for the practicing engineer who wants to expand into the arena of spatial data and distributed watershed modeling. It provides an integrated overview of the multiple facets of data-GIS-modeling issues and a source of background information for selection and application of GIS in watershed modeling. This first paper addresses selected spatial data issues, data structures and projections, data sources, and information on data resolution and uncertainties. Spatial data that are covered include digital elevation data, stream and drainage data, soil data, digital orthophoto data, remotely sensed data, and radar precipitation data. The focus is on data and issues that are common to many data-GIS-modeling applications. The second paper presents issues on and examples of GIS and hydrologic models and provides recommendations with respect to organization and implementation of the integrated use of spatial data, GIS, and distributed watershed models.

INTRODUCTION

Distributed watershed models are often used to quantify and solve water resources problems. In the 1970s and 1980s the routine application of these models had been frustrated by the need for large data sets to describe the spatial variability of many watershed characteristics. The increasing availability of spatial data in electronic format and geographic information system (GIS) software to manage and prepare spatial data has led to a renewed interest in the use of distributed watershed models. However, the recent proliferation of spatial data, GIS, and models for hydrologic applications has made it difficult for hydrologists and other practitioners to evaluate their value and choose among them. Also, this proliferation generates new questions with respect to the source, accuracy, storage requirements, and applicability of spatial data, GIS, and models. Although documentation and guidance can generally be found, it is dispersed in research reports, journal publications, the Internet, and user manuals, thus making a comprehensive review of this documentation difficult and often impractical. An integrated overview of important aspects of the data-GIS-model issue is needed to provide the practitioner with information on spatial data, GIS, and new approaches in distributed modeling, as well as capabilities and limitations affecting practical watershed modeling applications.

As a result of this need, the ASCE's Surface Water Hydrology Committee of the Division of Water Resources Engineering Division formed a task committee on GIS Modules and Distributed Models of the Watershed. The committee reviewed the current methods and data needs for GIS modules and distributed models, organized and sponsored sessions at specialty conferences, and prepared a report for the general practitioner (ASCE 1999). This paper summarizes the report, identifies types and sources of spatial data, discusses data quality concerns, illustrates GIS capabilities, and addresses GIS-model integration and implementation issues. This paper neither pretends to be nor can be a comprehensive treatment of the vast subject matter, yet it covers numerous relevant and interrelated aspects that are common to many data-GIS-modeling applications. Technical details have intentionally been omitted to maintain the focus on underlying issues and can be found in the cited literature. The purpose of this paper is to provide the practicing engineer who wants to expand into the arena of spatial data and distributed watershed modeling with an overview of the data-GIS-modeling issues and a source of background information for selection and application of GIS in watershed modeling. This paper is not intended for the expert, although it may serve as a useful reference. Because of the extent of the subject matter, the material is presented in two parts. Part I addresses spatial data issues, and part II addresses GIS/model integration and implementation issues.

In this first part, an introduction to vector and raster data structures is given, followed by a brief review of data projections. Thereafter, sources, quality, and limitations for topographic, surface drainage, orthophoto, and soil data are presented. The last section covers remotely sensed data and their potential use in distributed watershed modeling, as well as the availability, application potential, and shortcomings of distributed precipitation data from radar.

DATA STRUCTURES

Spatial data in GIS are most often organized into vector and raster data structures. In the vector structure, geographic features or objects are represented by points, lines, and polygons that are precisely positioned in a continuous map space, similar to traditional hard-copy maps that identify landmarks, buildings, roads, streams, water bodies, and other features by points, lines, and shaded areas. In addition, each object in the vector structure includes topologic information that describes its spatial relation to neighboring objects, in particular its connectivity and adjacency. This explicit and unambiguous definition of and linkage between objects makes vector structures attractive and allows for the automated analysis and interpretation of spatial data in GIS environments (Meijerink et al. 1994). On the other hand, raster structures divide space into a

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2D grid of cells, where each cell contains a value representing the attribute being mapped. Each grid cell is referenced by a row and column number, with the boundary of the grid being registered in space to known coordinates. A point is represented by a single grid cell, a line by a string of connected cells, and areas by a group of adjacent cells. The simplicity of data processing in raster structures and the readily available remotely sensed data in raster format have contributed to its popularity.

Vector and raster structures both have advantages and disadvantages. Vector structures are generally well suited to represent networks, connected objects, and features that are defined by distinct boundaries. Raster structures work best when the attributes they represent are continuously and smoothly varying in space. The complementary characteristics of both vector and raster structures have long been recognized. Modern GIS can process both structures, including conversion between structures and overlays of both structures. For distributed watershed modeling, many continuous and spatially variable land-surface attributes are acquired by remote sensing methods and are generally available in raster format, whereas digitized geographic features are generally provided in vector format. More often the choice of whether to use raster or vector data for a particular attribute is dictated by the structure in which the data are available, with raster data being more prevalent because of their simplicity of use and broader availability. However, in raster structures geographical features are not continuous, but quantized, which can have an important effect on the estimation of lengths and areas when grid cells are large with respect to the features being represented (Burrough 1986). Therefore, great care should be taken when selecting a resolution (cell size) for raster structures, in particular when physical properties of linear and areal features, such as stream networks, boundaries, or subcatchment areas, are being extracted. Increasing the resolution of a raster by subdividing the cells and smoothing the attribute values does not increase the information content of the raster and the approximation errors for length and area estimation remain, at best, unchanged from that of the original raster at the coarser resolution. Regardless of the structure and resolution in which the data are available, conversion from one structure to another can be performed to suit particular needs.

PROJECTIONS

The interface of distributed watershed models with GIS data describing the landscape requires the assembly of the spatial data from various sources into a consistent reference frame. All points on the earth's surface can be defined in geographic coordinates as latitude, longitude, and elevation above mean sea level. A map projection is a mathematical transformation by which the latitude and longitude of each point on the earth's curved surface are converted into corresponding (x, y) or (easting, northing) projected coordinates in a flat map reference frame (McDonnell 1991). If data are available in one map projection and required in another, specialized GIS software can perform the transformation into the new projected reference frame. Knowledge of map projections is perhaps the main subject that a civil engineer most lacks when entering the GIS field.

A map projection requires the specification of an earth datum, projection method, and set of projection parameters. Although the earth is commonly thought of as a sphere, it is actually an oblate spheroid or ellipsoid. All latitude and longitude coordinates are defined on an Earth datum, which includes a reference ellipse rotated around a defined axis of rotation. For the United States, two horizontal earth datums are in common use: the North American Datum of 1927 (NAD 27) and the North American Datum of 1983 (NAD 83). The conversion from NAD 27 to NAD 83 moves a particular point in latitude, longitude coordinates between 10 and 100 m, depending on location.

There are three main types of map projection methods: cylindrical, conical, and azimuthal (Snyder and Voxland 1989). A cylindrical projection involves enclosing the earth by a cylinder, projecting each point on the earth's surface onto a corresponding point on the surface of the cylinder, then unrolling the cylindrical surface to form a flat map. The best known projection of this kind is the Transverse Mercator projection, which forms the basis of the Universal Transverse Mercator (UTM) coordinate system, widely used in the United States for projections of states which have primarily a north-south orientation, such as California. A conical projection lays a cone over the earth, usually with the apex above the North Pole or below the South Pole, and then projects the points on the earth's surface onto the surface of the cone. The best known conical projection is the Lambert Conformal Conic projection, used in the United States for projections of land masses with primarily east-west extent, such as the United States as a whole and states such as Texas. Another conical projection important to hydrology is the Albers Equal Area projection, which preserves true earth surface area on the flat map projection. An azimuthal map projection is one in which a flat map surface touches the earth's surface at one point—this approach is used for meteorological mapping and for views of earth from space. Several standardized projection systems exist for legal purposes. In the United States, the most important of these is the State Plane Coordinate System, which defines for each state a set of one or more projection zones and the map projection and parameters for each zone (Snyder 1991). The State Plane System was developed during the 1930s and its projections are based on the NAD 27 datum and have coordinates in units of feet. More modern standardized projection systems use the NAD 83 datum and have coordinates in units of meters.

To plot a map, a decision as to map scale is needed. The map scale is the ratio between the distance in units of feet or meters of two points on the earth's surface and the corresponding distance between those two points on the plotted map. The most commonly used map scale for GIS data used in hydrology is the 1:250,000 scale for the national coverage of digital elevation model (DEM) data. State Soil Geographic (STATSGO) soils coverage, and U.S. Geological Survey (USGS) land-use/land-cover files. The 1:100,000 scale is used for the highest resolution of national coverage of digital line graphs of the U.S. stream network. The 1:24,000 scale is used for the standard USGS 7.5′ quadrangle maps, now also becoming available in scanned form as digital raster graphics (Maidment 1996).

DEMs

Over the last decades nearly all the United States has been digitized into grids of elevation values or DEMs. Topographic information that is needed by distributed watershed models such as slope, aspect, flow length, contributing area, drainage divides, and channel network can be rapidly and reliably extracted by GIS from DEMs.

DEMs are generally stored in one of three data structures: grid, triangulated irregular network (TIN), and contour based. Grid structures usually consist of a square grid matrix with an elevation value specified at each grid square, called a cell. Location is implicit from the row and column location within the matrix, provided that the boundary coordinates of the matrix are known. In TIN structures, a continuous surface is generated from interconnected triangles with known location and elevation values at the vertices of the triangles. These data are usually developed from aerial overflights and photogrammetric procedures or from grid DEM data. Triangles vary in size, with smaller triangles in areas of rapidly changing topography and larger triangles in areas of relatively smooth topography. Contour-based structures consist of digitized contour lines defined by a collection of *x*,*y*-coordinate pairs for contours of specified elevation. Topographic representation of this data structure is often referred to as a digital line graph (DLG).

Each of the DEM structures has its advantages and disadvantages (Moore et al. 1991). Square-grid DEMs are most widely used because of their simplicity, processing ease, and computational efficiency. Disadvantages include grid size dependency of certain computed landscape parameters and inability to adjust the grid size to changes in the size of landscape characteristics. Triangulated irregular networks overcome these disadvantages to some extent. However, the computation of landscape attributes from irregular triangles is more complex than for square-grid DEMs. Also, TINs are not as widely available as square-grid DEMs and they are often developed using square-grid DEM data as their initial elevation data source. Contour-based structures provide better outlines of landscape features than grid structures and are well suited to define streamlines and stream tubes of surface runoff. However, contours are 1D features and the representation of the 2D landscape continuum with DLGs generally requires considerably more data than representation by grid DEMs (Moore et al. 1991). The stated advantages and disadvantages of DEM structures are relative in the sense that what is considered an advantage for data storage may be a disadvantage for data processing. Nevertheless, DEMs are mostly available in the grid structure format.

The USGS offers a variety of digital elevation data products (USGS 1990). These include the 7.5′ grid DEM data, which have a grid spacing of 30 × 30 m, USGS 1° DEM data, which have a grid spacing of 3″ × 3″, and USGS 30′ DEM data, which have a grid spacing of 2″ × 2″ (USGS 1990). Recently, the USGS has begun the production of the 7.5′ DEMs at a 10 × 10 m resolution with a vertical resolution of 1 dm. However, at this time the coverage provided by this newest product is sparse. Other sources for DEM data include the National Imagery and Mapping Agency (formerly the Defense Mapping Agency) and the National Geophysical Data Center of the National Oceanic and Atmospheric Administration (NOAA). Custom DEM data can also be obtained through commercial providers, and new technologies, such as laser altimetry (Ritchie 1995) and radar interferometry (Zebker and Goldstein 1986) are currently being considered for production of global high quality and high resolution DEMs (Gesch 1994).

DEM data produced by the USGS are classified into one of three levels of quality (USGS 1990). Level 1 classification is generally reserved for data derived from scanning by the National High-Altitude Photography Program, National Aerial Photography Program, or equivalent photography. Level 2 classification is for elevation data sets that have been processed or smoothed for consistency and edited to remove identifiable systematic errors. DEM data derived from hypsographic and hydrographic data digitizing are entered into the Level 2 classification. Level 3 classification is derived from DLG data by using selected elements from both hypsography (contours and spot elevations) and hydrography (lakes, shorelines, and drainage). If necessary, ridge lines and hypsographic effects of major transportation features are also included in the derivation. Note that the availability of Level 3 is very limited.

The two important aspects in the selection of a DEM for hydrologic modeling are the quality and resolution of the DEM data. Quality refers to the accuracy of the elevation data, and resolution refers to the horizontal grid spacing and vertical elevation increment. Quality and resolution must be consistent with the scale and model of the physical process under consideration and with the study objectives. For many applications of physical-process based environmental models, the USGS 30 × 30 m DEM data (Levels 1 and 2) has broad accuracy standards and a rather coarse resolution with documented shortcomings [Ostman 1987; Topographic Science Working Group (TSWG) 1988; Garbrecht and Starks 1995). In particular, surface drainage identification is difficult in low-relief landscapes, as is derivation of related information such as slope and landform curvature. Research is under way to assess the impact of accuracy limitations, noise, and low resolution of DEM data on modeling results. Some preliminary results have been reported in the literature [for example, Wolock and Price (1994) and Zhang and Montgomery (1994)]. However, no firm guidelines are available for selection of DEM characteristics. The selection for a particular application is often driven by data availability, judgment, experience, and test applications.

STREAM AND DRAINAGE DATA

Surface drainage information is generally provided in the form of digitized stream data or drainage maps. Digitized stream data are often available from commercial and government sources or can be digitized directly by the user from maps. On the other hand, surface drainage maps, including drainage divides and stream networks, can also be generated from DEMs.

Digitized Stream Data

Digitized stream data are developed from maps, photographs, or surveys of the land. The data generally provide good detail to accurately represent the location, length, and connectivity of the stream network in the watershed. This stream data can be used as an overlay with other watershed grid data to segment the topography along drainage boundaries. In addition to the physical location of the streams in a watershed, other channel attributes, such as channel geometry and roughness characteristics, are sometimes provided in separate attribute tables. Acquisition of digitized stream data is generally inexpensive and can prove to be valuable for applications of distributed watershed models. The shortcoming of digitized stream data relates primarily to available resolutions. The stream information is usually in a specified resolution that may or may not suit the user’s needs. Further manipulation may be necessary to add or remove stream segments to adequately represent application-specific stream network features. Also, the necessary attribute files are not always available or may not contain all the desired information. Note that the position of digitized stream data may not always agree with related information from DEMs and other coverages. In these cases the user should reconcile inaccurate data sets with the data set deemed most reliable.

Popular sources of digitized stream data are the USGS, U.S. Environmental Protection Agency (USEPA), or commercial vendors. File formats for the USGS and USEPA data sets are standard formats that most GISs can interpret. The USGS provides several categories of landscape data in the form of DLGs. The hydrographic category includes streams, channels, lakes, and wetlands. This information is provided as digital vectors at various scales. Large-scale DLGs are derived from the USGS 1:20,000-, 1:24,000-, and 1:25,000-scale 7.5′ topographic quadrangle maps. Intermediate-scale DLGs are derived from USGS 1:100,000-scale 30′ × 60′ quadrangle maps. In addition, small-scale DLGs are derived from the USGS 1:200,000-scale sectional maps of the National Atlas of the United States of America. The hydrographic data contain full topological linkages in node, line, and area elements (USGS 1990, 1992, 1993; also, 〈http://edcwww.cr.usgs.gov/glis/gli.html〉).

Stream and channel network data can also be obtained from the STORET User Assistance Group, USEPA Office of Water (STORET is the USEPA's national water quality system and stands for STOrage and RETrieval system for water and biological monitoring data). The USEPA stream and channel network databases are called the River Reach Files. River Reach Files are a series of national hydrologic databases that uniquely identify and interconnect the stream segments or reaches that constitute the nation's surface water drainage system. The three versions of the Reach File that currently exist, known as RF1, RF2, and RF3-Alpha, respectively, were created from increasingly detailed sets of digital hydrographic data produced by the USGS. The USEPA enhanced these hydrographic data sets by assigning a unique reach code to each stream segment, determining the upstream/downstream relationships of each reach, and when possible, identifying the stream name for each reach. The structure and content of the Reach File databases were created expressly to establish hydrologic ordering, perform hydrologic modeling applications, and provide a unique identifier for each surface water feature. A variety of other reach-related attributes that support mapping and spatial analysis applications are also available (USEPA 1992, 1994; also, [http://www.epa.gov/owowwtr1/nps/gis/reach/html〉).

Another method of obtaining vector data is to digitize the information from existing maps. In this manner, one can choose the level of detail that is most appropriate to meet the specific needs of the project. If no adequate map exists, or if field verification of a map is desired, then a field survey could be performed to create a data set containing the desired stream and river network.

Hydrography and Drainage Information Derived from DEMs

Automated extraction of surface drainage, channel network, drainage divides, and other hydrographic data from DEMs has established itself as a result of increasing availability of square-grid DEMs and GIS software products that derive this data from DEMs (Jenson and Domingue 1988; Mark 1988; Moore et al. 1991; Martz and Garbrecht 1992, 1993). The automated techniques are faster and provide more precise and reproducible measurements than traditional manual techniques applied to topographic maps (Tribe 1991). Several methods exist for computing hydrographic data from DEMs. The D8 method (O'Callaghan and Mark 1984) is a single flow direction method where each cell discharges or spills onto one of its eight neighbors, the one located in the direction of steepest descent. The Rho8 method (Fairfield and Leymarie 1991) is a single flow-direction method similar to the D8 method, with the difference that it determines the receiving cell among the neighboring cells based on a probabilistic approach. The Lea method (1992) is also a single flow-direction method and routes the flow according to local aspect. There are also a number of multiple flow-direction methods (Freeman 1991; Quinn et al. 1991; Costa-Cabral and Burges 1994) that distribute flow from a cell among all of its lower-elevation neighbor cells, according to some specified rule. Although the multiple flow-direction algorithm seems to give superior results in the headwater region of a source channel and on convex hillslopes, a single flow-direction algorithm provides similar results in regions of convergent flow and along well-defined valleys (Freeman 1991; Quinn et al. 1991). This is usually the case in distributed watershed modeling, and the widely used D8 method is selected for discussion of the derivation of hydrographic data from square-grid DEMs.

D-8 Processing Method

The D-8 method (Fairfield and Leymarie 1991) identifies the steepest downslope flow path between each cell of a DEM and its eight neighbors and defines this path as the only flow path leaving the raster cell. The drainage network is identified by selecting a threshold catchment area at the bottom of which a source channel originates and classifying all cells with a greater catchment area as part of the drainage network. This drainage network identification approach is simple and directly generates connected networks. The D-8 method, as well as many other approaches, has difficulties identifying surface drainage in the presence of depressions, flat areas, and flow blockages (Garbrecht and Starks 1995). These features are often the result of data noise, interpolation errors, and systematic production errors in DEM elevation values. Such features occur in most DEMs and are viewed as spurious, mainly because of their predominantly numerical origin. It is common practice to remove the depressions and flat areas prior to drainage identification. Further information on removing closed depressions and flat areas can be found in Jenson and Domingue (1988), Tribe (1991), Garbrecht and Martz (1997), and Martz and Garbrecht (1999).

Drainage Network Extraction

A drainage network can be extracted from a DEM with an arbitrary drainage density or resolution (Tarboton et al. 1991). The characteristics of the extracted network depend very much on the definition of channel sources on the digital landscape. Once the channel sources are defined, the essential topology and morphometric characteristics of the corresponding downstream drainage network are predefined because of their close dependence on channel source definition. Thus, the proper identification of channel sources is critical for extraction of representative drainage networks from DEMs. The fundamental concepts that deal with channel initiation can readily be found in the literature (Montgomery and Dietrich 1988, 1989, 1992). The two prevailing methods for identification of network sources in DEMs are summarized in the next paragraphs.

The constant threshold area method assumes that channel sources are located at the transition from an increasing (convex) longitudinal slope profile on hillslopes to a decreasing (concave) longitudinal slope profile for channels. The constant threshold area method has found widespread application (Band 1986; Zevenberger and Thorne 1987; Morris and Heerdegen 1988; Gardner et al. 1991) and the use and implication of this method are discussed by Tarboton et al. (1991) and Montgomery and Foufoula-Georgiou (1993). The slope-dependent critical support area method assumes that the channel source represents an erosional threshold. This assumption implies that the channel source is the result of a change in sediment transport processes from sheet flow to concentrated flow, rather than a spatial transition in longitudinal slope profiles. This method was presented by Montgomery and Foufoula-Georgiou (1993) and is based on the channel initiation work by Dietrich et al. (1993).

Garbrecht and Martz (1995) broadened the applicability of the constant threshold area method by allowing the threshold area to vary within the DEM. This is particularly useful in large watersheds in which geology and drainage network characteristics display distinct spatial patterns. Another issue that is often of concern with drainage networks extracted from DEMs is the precise positioning of channels in the digital landscape. Comparison with actual maps or areal photos often shows discrepancies, particularly in low-relief landscapes. The primary reason for this discrepancy is the approximate nature of digital landscapes, which cannot capture important topographic information that is below the DEM resolution. Although the channel position in the digital landscape is consistent with the digital topography, it may not reflect the actual drainage path in the field. Newer DEMs are generally hydrographically corrected and lead to extracted channel networks that are positioned similar to the blue lines on the traditional USGS maps.

Drainage Network Topology

For raster images of the channel network to be useful in hydrologic and runoff modeling, individual channels and adjacent contributing areas must be explicitly identified by a number (index) and associated with topologic information for upstream and downstream connections. Such channel indexing is often possible in vector GIS but usually not in raster GIS. Yet, indexing and organizing the channel network in a sequence that is meaningful for flow routing is fundamental for automated linkage of raster GIS information of the network and traditional surface runoff modeling. Garbrecht and Martz (1997) have proposed an algorithm that interprets a GIS raster image of a network, indexes the channel links and network nodes, and organizes the channels into a sequence for cascade flow routing (Garbrecht 1988).

SOIL DATA

Soil data at state and county scales are available from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service. At the state scale, soil maps are made for the STATSGO database (mapping scale 1:250,000). The level of mapping is designed to be used for broad multicounty resource planning, management, and monitoring at river basin, regional, and state scales. The data are not detailed enough for county-level interpretations. STATSGO data are available for the conterminous United States, Hawaii, and Puerto Rico. Composition of soil map units was coordinated across state boundaries, and data match at state boundaries. Each STATSGO map is linked to the Soil Interpretations Record attribute database. The Soil Interpretations Record database includes >25 physical and chemical soil properties, interpretations, and productivity. Examples of information that can be queried from the database are available water capacity, soil reaction, salinity, flooding, water table, and bedrock, and interpretations for engineering uses, cropland, woodland, rangeland, pastureland, wildlife, and recreation development. The data can be downloaded from the Internet, including description and data user guide (USDA 1991), at ⟨http://www.ftw.nrcs.usda.gov/soils_data.html⟩.

At the county scale, the Soil Survey Geographic (SSURGO) database includes soil maps at scales generally ranging from 1:12,000 to 1:63,360. SSURGO is the most detailed level of soil mapping done by the NRCS. This level of mapping is designed for use by farmers, ranchers, landowners, and townships for county-scale natural resource planning and management. SSURGO data are available for selected counties and areas throughout the United States and its territories. With the attribute data, this soils database serves as an excellent reference for determining erodible areas and developing erosion control practices, reviewing site development proposals and land-use potential, making land-use assessments, and identifying wetlands and sand and gravel aquifer areas (USDA 1995). SSURGO data are collected and archived in 7.5′ quadrangle units and distributed as complete coverage for a soil survey area. SSURGO is linked to a Map Unit Interpretations Record (MUIR) attribute database. The MUIR database includes >25 physical and chemical soil properties, similar to the STATSGO attribute database. The data can be downloaded from the Internet, including description and data user guide (USDA 1995), at ⟨http://www.ftw.nrcs.usda.gov/ssur_data.html⟩.

Individual soil series level digital data required for detailed hydrologic modeling are generally not readily available and need to be either scanned or digitized from the original county soil surveys. The NRCS is in the process of performing this on a county-by-county level as the need arises and makes these data available at a marginal cost. These data typically need associated look-up tables that assign hydrologic soil groups and properties for hydrologic modeling.

DIGITAL ORTHOPHOTO DATA

A National Digital Orthophoto Program was initiated in 1990 to ensure the public domain availability of digital orthophoto quadrangle (DOQ) data for the nation. A DOQ is a computer-generated image of an aerial photograph, in which displacements caused by camera orientation and terrain have been removed. These products combine the image characteristics of a photograph with the geometric qualities of a map and can be used in numerous GIS applications either alone or combined with other digital data.

The standard DOQs produced by the USGS are either grayscale or color-infrared images with a 1-m ground resolution. They cover an area measuring 3.75′ longitude × 3.75′ latitude, or approximately 5 mi on each side. Each DOQ has between 50 and 300 m of overedge image beyond the latitude and longitude corner crosses embedded in the image. This overedge facilitates tonal matching and mosaicking adjacent images. All DOQs are referenced to NAD 83 and cast on the Universal Transverse Mercator (UTM) projection.

DOQs are distributed in either standard or GeoTIFF format on a variety of media. DOQ files can be obtained from the USGS Sales Data Base and can be ordered on-line through the Global Land Information System at ⟨edcwww.cr.usgs.gov/webglis⟩ or by contacting the Earth Science Center. DOQ coverage is not available for all areas in the United States.

REMOTE SENSING DATA

Remote sensing uses measurements of the electromagnetic spectrum to characterize the landscape or infer properties of it, or in some cases, actually measure hydrologic state variables. Remote sensing provides the unique capability to represent the spatial distribution of variables. These data are generally in raster format, which simplifies their incorporation into GIS. Studies have shown that, for planning applications, remotely sensed data can be cost-effective (Jackson et al. 1977). Sources of satellite data can be found at the following popular Web sites: ⟨http//radarsat.space.gc.ca⟩, ⟨http://spaceimage.com⟩, ⟨http://www.spot.com⟩, and ⟨http://daac.gsfc.nasa.gov⟩. These sites provide complete information of data specifications, availability, cost, ordering information, and sources of less commonly used data. Some of the traditional and unique remote-sensing derived variables for scientific hydrology are discussed below. These include precipitation, land use and cover, vegetation indices and leaf area index, drainage patterns, surface temperature, soil moisture, and snow. For an in-depth coverage of general remote sensing applications to hydrology, the reader is referred to a UNESCO publication (Schultz and Barrett 1989), World Meteorological Organization report (Kuittinen 1992), and general introductory books on remote sensing (Lillesand and Kiefer 1987; Engman and Gurney 1991; Schultz and Engman 2000).

Precipitation

For the practicing hydrologist, satellite rainfall methods are most valuable when there are no or very few surface gauges or radar measurements. This is usually the case for projects situated abroad in countries with limited historical precipitation data. Satellite images of the visible and infrared spectrum can be used to estimate rainfall by relating cloud characteristics to instantaneous rainfall rates and cumulative rainfall over time (Barrett 1970; Papadakis et al. 1993). The latest review of ground-based and satellite remote sensing of rainfall can be found in Schultz and Engman (2000). However, for the continental United States, either gauge rainfall data from the National Weather Service stations or from radar (see below) are usually available.

Land Cover/Use

Land cover/use is perhaps the category in which remote sensing has made its largest impact and comes closest to maximizing the capabilities of remote sensing. The degree of urban land use or various categories of agricultural or forest can be determined accurately through remote sensing. Typically, the development of such maps requires that a limited ground survey (called ground referencing) be conducted in the area of interest in order to establish the relationship between the actual ground observation and the reflectance measured by the remote sensing device. The ground truth data (i.e., cover type) and location of the known surface are entered into an image processing computer program and areas of similar reflectance are assigned to a known ground-cover type. For large areas, it is often impractical to conduct even a limited ground survey. Therefore, a computer program is generally used to conduct an unsupervised classification of the remotely sensed image whereby areas of similar reflectance are assigned the same land-cover category, which later is named by a knowledgeable person. In general, land-cover/use accuracy is directly related to the spatial resolution of the sensors, which range from about 10 m to 1 km. SPOT Image Corp. produces a customer-specified commercial land-cover classification product, available by means of the Internet at ⟨http://www.spot.com⟩. Another source of land-cover/use data includes the EROS Data Center located in Sioux Falls, S. Dak. and with a Web site at ⟨http://edcwww.cr.usgs.gov/eros-home.html⟩. A more complete listing of potential satellite data, revisit times, and spatial and spectral resolutions is given by Schultz and Engman (2000).

Vegetation Indices

Vegetation indices such as the normalized difference vegetation index (NDVI) (Tucker et al. 1979) and leaf area index have been shown to be related to evaporation coefficients such as the crop coefficient (defined as the ratio of actual evaporation to reference crop evaporation) and the transpiration coefficient (defined as the ratio of unstressed evaporation and reference crop evaporation). The NDVI index can be calculated from any sensor having red and near-infrared wave bands. For example A Very High Resolution Radiometer sensor (AVHRR) leads to NDVI products that have a spatial resolution of about 1 km. The AVHRR provides daily coverage, but one often finds weekly and biweekly NDVI maps (e.g., the Kansas Applied Remote Sensing Program's Green Report, ⟨http://www.kars.ukans.edu⟩). Data sources for the NDVI include the EROS Data Center (see above) and NOAA's National Environmental Satellite Data Information Service (at ⟨http://ns.noaa.gov/nesdis⟩). A more complete disussion of these indices and their applications to hydrology can be found in Bastiaanssen (1998) and Schulz and Engman (2000).

Drainage Basin and Stream Network

Satellite remote sensing can provide valuable sources of data for delineating drainage basins and stream networks as well as inventories of surface water bodies and storages. Satellites using the visible and near-infrared regions of the spectrum can provide detailed information of the basin characteristics, and SPOT with its stereo capability can even provide topographic information (Gugan and Dowman 1988). Side Looking Airborne Radar (SLAR) and satellite SARs can produce very detailed maps of basin characteristics, even in traditionally cloudy areas and areas with heavy vegetation growth. Interferometric SAR also can provide quantitative measures of topography.

Surface Temperature

Surface temperatures measured by thermal infrared sensors have been used to estimate evaporation directly or as a variable in a more complex model. Price (1982) has demonstrated how thermal data from the Heat Capacity Mapping Mission could be used to estimate regional evapotranspiration, which was comparable to pan-evaporation data. Ottle et al. (1989) have shown how satellite-derived surface temperatures can be used to estimate evapotranspiration and soil moisture in a model that has been modified to use these data.

Soil Moisture

Recent advances in remote sensing technology have shown that soil moisture can be quantitatively measured under a variety of topographic and vegetation cover conditions. Microwave techniques for measuring soil moisture include both the passive and the active microwave approaches, with each having distinct advantages. At present, most microwave radiometers built to detect soil moisture are in the experimental phase, where much of the research is being conducted to develop and verify soil moisture retrieval algorithms. Soil moisture products are not generally available, and it should be pointed out that those that are available only yield the soil moisture in the top 5 cm of the soil profile.

Snow

Extent of snow cover is easily determined with VIS/NIR data that offer an additional feature in that one can observe even the most remote regions that are generally inaccessible during the winter months. Although snow cover does not provide the most important information about the snow, that of its depth and water content, these frequently can be inferred from time series of snow cover maps known as snow cover depletion curves (Hall and Martinec 1985) or from simple regression equations (Rango et al. 1975). Currently, NOAA develops weekly digital snow cover maps for about 4,000 river basins in North America, of which approximately 300 are mapped according to elevation for use in streamflow forecasting (Carroll and Holroyd 1990). NOAA also produces regional and global maps of mean monthly snow cover. A complete list of NOAA snow products and services can be found on their World Wide Web page at ⟨http://www.nohrsc.nws.gov⟩.

Future Developments and Integration with GIS

Continuing high spatial resolution data from the Landsat and SPOT satellites, passive microwave data from the Special Sensor/Microwave Imager (SS/MI), and continuing meteorological satellite coverage from the NOAA, GOES, GMS, and Meteosat series all mean that the remotely sensed techniques described above will continue to be employed and expanded upon. New sensors, particularly in the microwave region, promise great potential for hydrologic applications. Many new observations of the hydrologic cycle will be available from new satellite systems, and concurrently, new models will allow the data to be analyzed and addressed in ways that previously represented intractable problems. The raster format of digital remote sensing data also makes the data ideal for merging with a GIS. The GIS allows for the combining of other spatial data forms such as topography, soil maps as hydrologic variables such as rainfall distributions, or soil moisture (Kouwen et al.

1993; Schultz and Engman 2000). Examples of other approaches can be found in Fortin and Bernier (1991), Ott et al. (1991), Schultz (1993), and Mauser (1996).

PRECIPITATION DATA FOR HYDROLOGIC MODELING

Rain Gauge Data

Rainfall data are archived by the NOAA National Climatic Data Center (NCDC) located in Asheville, N. C. The NCDC data holdings can be accessed at the World Wide Web address: 〈http://www.ncdc.noaa.gov〉. Precipitation data from NCDC include daily rainfall from the cooperative National Weather Service (NWS) stations, hourly rainfall rates at first-order NWS meteorological stations, and quarterly (15-min) rainfall rates at selected stations around the United States. The period of record for these quarterly rainfall data is quite variable, with few stations installed before 1970. The NCDC data can also be obtained through commercial vendors that produce CD-ROMs containing NCDC precipitation data and proprietary software to display, process, and retrieve the data. Rainfall data are also collected by a host of private companies, water-supply districts, university researchers, and government agencies for individual projects. This potential source of precipitation data varies from region to region and requires significant research to identify local sources.

Radar-Rainfall Estimates

The NWS has deployed >120 weather surveillance radar, 1988-Doppler (WSR-88D) radar stations, also known as NEXRAD radar (Klazura and Imy 1993). The WSR-88D radar stations provide continuous radar coverage <3,000 m above sea level, except where rising terrain obstructs the radar beam.

Hourly digital precipitation array data generated by the WSR-88D radar is the most suitable for watershed modeling. Three stages of precipitation processing occur in the production of the digital precipitation array product. Stage I processing includes automated quality controls to correct for reflectivity outliers, beam blockages, and spurious reflectivity echoes. The end result is a composite reflectivity that is converted to precipitation rates using a rainfall-reflectivity (*Z-R*) relationship. The rainfall rates are accumulated over time to produce hourly accumulations that are adjusted based on concurrently measured precipitation gauge data. During Stage II processing, various satellite and ground observations are compared with the radar data to identify and correct errors caused by anomalous propagation and other spurious radar echoes. During Stage III processing, data from a number of radar sites are merged together to form a complete mosaic over a large area and remaining identifiable errors are corrected. This is the final step in a complex process to generate the best possible quantitative estimates of precipitation, which has the potential to be used as input to hydrologic models (Shedd et al. 1992).

Free and open access to the radar-rainfall data is limited. However, WSR-88D data can be obtained from NCDC and related products are available from a number of commercial vendors by means of the NEXRAD Information Dissemination Service (NIDS). There are four authorized NIDS vendors, each of which offers a variety of radar data products. The vendors are Kavouras Inc., Paramax Systems Corp., WSI Corp., and Zephyr Weather Information Service, Inc. Data from NWS and university research radar stations can be obtained for selected events by arrangement. Research radar stations do not operate continuously and are therefore of little use for operational hydrology.

Radar-Rainfall Accuracy

Radar-rainfall estimates in engineering hydrology are still experimental, as questions remain regarding the effect of radar-rainfall estimation errors on runoff modeling. There are numerous sources of radar-rainfall estimation errors, as discussed by Wilson and Brandes (1979), Zawadzki (1982, 1984), Austin (1987), Krajewski and Smith (1991), and Smith and Krajewski (1993), among others. For example, the magnitude of the radar reflectivity factor Z is completely dominated by the largest particles in the radar beam. Also, the presence of wet hail or snow masks useful information regarding liquid rain rates. Recent articles have shown that radar-rainfall estimates augmented with information from sparse rain gauge networks are useful for hydrologic analysis (Smith et al. 1996; Steiner et al. 1997) and that, under optimal conditions, radar-rainfall estimates compare quite well with ground observations of precipitation after being adjusted using rain gauge observations. However, at this time, most weather radar stations in the United States have not been calibrated against a location specific standard. Calibration errors can be significant and cause observations of precipitation from two different radar stations at the same range from the storm to differ. For this reason, the practical application of radar-rainfall estimates should include validation against available rain gauge observations.

WSR-88D Data Coordinate Conversion Issues

WSR-88D radar data are georeferenced using the Hydrologic Rainfall Analysis Project coordinate system (Klazura and Imy 1993). The grid resolution for WSR-88D radar data is often described as being on a 4×4 km grid. In reality, the mesh length depends on the latitude, with the grid spacing varying between approximately 3.5 and 4.5 km within the contiguous United States. When using radar rainfall data in a distributed hydrologic modeling application, the radar data must be properly georeferenced. To do so, data are typically converted from the Hydrologic Rainfall Analysis Project coordinate system to that of the hydrologic model application by means of a standard set of transformation equations.

SUMMARY AND CONCLUSIONS

Advances in computational power and the growing availability of spatial data have made it possible to accurately describe watershed characteristics for distributed modeling of the watershed hydrology. This paper provides an overview of selected spatial data topics that are important to the integrated data-GIS-modeling approach. The intent of this paper is to assist the uninitiated practitioner in the identification of data availability, sources, specifications, and processing needs, as well as in the recognition of data limitations and uncertainties. This paper is neither a comprehensive nor a detailed treatment of the vast subject matter. However, it covers a selection of relevant and interrelated aspects that are common to many data-GIS-modeling applications. The following important conclusions can be drawn from this spatial data review:

- The recent explosion of spatial data and processing software provide many new opportunities to represent and visualize watershed characteristics in a distributed fashion and to conduct the hydrologic investigation based on a distributed approach.
- Spatial data are produced by a growing number of federal, state, and commercial organizations. The acquisition of this data often requires a time-consuming ‘‘search and discovery’’ approach. This paper and its references provide an initial source of information regarding spatial data.
- The spatial data are often provided by the different sources in different data structures, formats, and resolutions. Processing and conversion of the data into a consistent projection, format, and resolution is often needed for practical applications.

- Many traditional spatial data are static, such as the soil data, digital elevation data, and watershed drainage characteristics. However, increasing satellite and radar data capabilities provide data sets of watershed characteristics that change with time, such as seasonal vegetation indices, hourly/daily precipitation values, and ground surface temperature values.

This paper helps the practitioner with understanding the practices and issues of using spatial data for hydrologic modeling. The second part of this paper, entitled ''Modules, Applications and Implementation Issues'' (Ogden et al. 2001) presents a number of applications and models that can take advantage of spatially distributed GIS data. It provides practitioners with background on implementation issues to help them choose suitable applications that meet their needs.

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REFERENCES

ASCE Task Committee on GIS Modules and Distributed Models of the Watershed. (1999). ''Geographic information system modules and distributes models of the watershed.'' Reston, Va.

Austin, P. M. (1987). ''Relation between measured radar reflectivity and surface rainfall.'' *Monthly Weather Rev.*, 115(5), 1053–1069.

Band, L. E. (1986). ''Topographic partitioning of watersheds with digital elevation models.'' *Water Resour. Res.*, 22(1), 15–24.

Barrett, E. C. (1970). ''The estimation of monthly rainfall from satellite data.'' *Monthly Weather Rev.*, 98, 322–327.

Bastiaanssen, W. G. M. (1998). ''Remote sensing in water resources management: The state of the art.'' International Water Management Institute, Columbo, Sri Lanka.

Burrough, P. A. (1986). *Principles of geographic information systems for land resources assessment, Oxford Sci. Publ., Monographs on Soil and Resour. Survey No. 12*, Oxford University Press, New York.

Carroll, T. R., and Holsoyd, E. W., III. (1990). ''Operational remote sensing of snow cover in the U.S. and Canada.'' *Hydraulics/hydrology of arid lands*, R. H. French, ed., ASCE, New York, 286–291.

Costa-Cabral, M. C., and Burges, S. J. (1994). ''Digital elevation model networks (DEMON): A model of flow over hillslopes for computation of contributing and dispersal areas.'' *Water Resour. Res.*, 30(6), 1681–1692.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., and McKean, J. (1993). ''Analysis of erosion thresholds, channel networks and landscape morphology using a digital terrain model.'' *J. Geol.*, 101(2), 259–278.

Engman, E. T., and Gurney, R. J. (1991). *Remote sensing in hydrology*, Chapman & Hall, London.

Fairfield, J., and Leymarie, P. (1991). ''Drainage networks from grid digital elevation models.'' *Water Resour. Res.*, 30(6), 1681–1692.

Freeman, T. G. (1991). ''Calculating catchment area with divergent flow based on a regular grid.'' *Comp. and Geosciences*, 17(3), 413–422.

Garbrecht, J. (1988). ''Determination of the execution sequence of channel flow for cascade routing in a drainage network.'' *Hydrosoft*, 1(3), 129–138.

Garbrecht, J., and Martz, L. W. (1995). ''Advances in automated landscape analysis.'' *Proc., 1st Int. Conf. on Water Resour. Engrg.*, W. H. Espey and P. G. Combs, eds., Vol. 1, ASCE, New York, 844–848.

Garbrecht, J., and Martz, L. W. (1997). ''The assignment of drainage direction over flat surfaces in raster digital elevation models.'' *J. Hydro.*, Amsterdam, 193(1-4), 204–213.

Garbrecht, J., and Starks, P. (1995). ''Note on the use of USGS Level 1 7.5-minute DEM coverages for landscape drainage analyses.'' *Photogrammetric Engrg. and Remote Sensing*, 61(5), 519–522.

Garbrecht, J., Starks, P. J., and Martz, L. W. (1996). ''New digital landscape parameterization methodologies.'' *Proc., AWRA Annu. Symp. on GIS and Water Resour.*, American Water Resources Association, Middleburg, Va., 357–365.

Gardner, T. W., Sasoswky, K. C., and Day, R. L. (1991). ''Automated extraction of geomorphic properties from digital elevation data.'' *Geomorphology Supplements*, 80, 57–68.

Gesch, D. B. (1994). ''Topographic data requirements for EOS global change research.'' *Open-File Rep. 94-626*, U.S. Geological Survey, Department of the Interior, Washington, D.C.

Gugan, D. J., and Dowman, I. J. (1988). ''Topographic mapping from SPOT imagery.'' *Photogrammetric Engrg. and Remote Sensing*, 54(12), 1409–1414.

Hall, D. K., and Martinec, J. (1985). *Remote sensing of ice and snow*, Chapman & Hall, London.

Jackson, T. J., Fitch, W. N., and Ragan, R. M. (1977). ''Test of Landsat-based urban hydrologic modeling.'' *J. Water Resour. Plng. and Mgmt. Div.*, ASCE, 103(1), 141–158.

Jenson, S. K., and Domingue, J. O. (1988). ''Extracting topographic structure from digital elevation data for geographical information system analysis.'' *Photogrammetric Engrg. and Remote Sensing*, 54(11), 1593–1600.

Klazura, G. E., and Imy, D. A. (1993). ''A description of the initial set of analysis products available from the NEXRAD WSR-88D system.'' Bull. Am. Meteor. Soc., 74(7), 1293–1311.

Kouwen, N., Soulis, E. D., Pietroniro, A., Donald, J., and Harrington, R. A. (1993). ''Grouped response units for distributed hydrologic modeling.'' *J. Water Resour. Plng. and Mgmt.*, ASCE, 119(3), 289–305.

Krajewski, W. F., and Smith, J. A. (1991). ''On the estimation of climatological Z-R relationships.'' *J. Appl. Meteorology*, 30(10), 1436–1445.

Kuittinen, R. (1992). ''Remote sensing for hydrology, progress and prospects,'' *Operational Hydro. Rep. No. 36*, World Meteorological Organization, Geneva.

Lea, N. L. (1992). ''An aspect driven kinematic routing algorithm.'' *Overland flow: Hydraulics and erosion mechanics*, A. J. Parson and A. D. Abrahams, eds., Chapman & Hall, New York.

Lillesand, T. M., and Kiefer, R. W. (1987). *Remote sensing and image interpretation*, 2nd Ed., Wiley, New York.

Maidment, D. R. (1996). ''GIS and hydrologic modeling—An assessment of progress.'' *Proc., 3rd Int. Conf./Workshop on Integrating GIS and Envir. Modeling*, Geographical Information and Analysis, Santa Barbara, Calif. (CD-ROM).

Mark, D. M. (1988). ''Network models in geomorphology.'' *Modeling geomorphological systems*, M. G. Anderson, ed., Wiley, Chichester, U.K., 73–96.

Martz, L. W., and Garbrecht, J. (1992). ''Numerical definition of drainage network and subcatchment areas from digital elevation models.'' *Comp. and Geosciences*, 18(6), 747–761.

Martz, L. W., and Garbrecht, J. (1993). ''Automated extraction of drainage network and watershed data from digital elevation models.'' *Water Resour. Bull.*, 29(6), 901–908.

Martz, L. W., and Garbrecht, J. (1999). ''An outlet breaching algorithm for the treatment of closed depressions in a raster DEM.'' *Comp. and Geosciences*, 25(7), 835–844.

Mauser, W. (1996). ''Mesoscale modeling of evapotranspiration using remote sensing data.'' *Proc., Europto series*, Vol. 2959, SPIE, Taormina, Italy, 108–117.

McDonnell, P. W. (1991). *Introduction to map projections*, 2nd Ed., Landmark Enterprises, Rancho Cordova, Calif.

Meijerink, A. M. J., de Bouwer, H. A. M., Mannaerts, C. M., and Valenzuela, C. R. (1994). ''Introduction to the use of geographic information systems for practical hydrology.'' *Publ. No. 23*, International Institute for Aerospace Survey and Earth Sciences, Emschede, The Netherlands.

Montgomery, D. R., and Dietrich, W. E. (1988). ''Where do channels begin?'' *Nature*, 36(6196), 232–234.

Montgomery, D. R., and Dietrich, W. E. (1989). ''Source areas, drainage density, and channel initiation.'' *Water Resour. Res.*, 25(8), 1907–1918.

Montgomery, D. R., and Dietrich, W. E. (1992). ''Channel initiation and the problem of landscape scale.'' *Sci.*, 225, 826–830.

Montgomery, D. R., and Foufoula-Georgiou, E. (1993). *Water Resour. Res.*, 29(12), 3925–3934.

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

Mooris, D. G., and Heerdegen, R. G. (1988). ''Automatically derived

catchment boundary and channel networks and their hydrological applications.'' *Geomorphology*, 1(2), 131–141.
O'Callaghan, J. F., and Mark, D. M. (1984). ''The extraction of drainage networks from digital elevation data.'' *Comp. Vision, Graphics, and Image Processing*, 28, 323–344.
Ogden, F. L., Garbrecht, J., DeBarry, P. A., and Johnson, L. E. (2001). ''GIS and distributed watershed models. II: Modules, interfaces, and models.'' *J. Hydrologic Engrg.*, ASCE, 6(6), 515–523.
Ostman, A. (1987). ''Accuracy estimation of digital elevation data banks.'' *Photogrammetric Engrg. and Remote Sensing*, 53(4), 425–430.
Ott, M. Su, Z., Schumann, A. H., and Schultz, G. A. (1991). ''Development of a distributed hydrological model for flood forecasting and impact assessment of land use change in the international Mosel River basin.'' *Proc., Vienna Symp. IAHS Publ. No. 201*, International Association of Hydrological Sciences, Wallingford, U.K.
Papadakis, I., Napiorkowski, J., and Schultz, G. A. (1993). ''Monthly runoff generated by non-linear model using multispectral and multitemporal satellite imagery.'' *Adv. Space Res.*, 13(5), 181–186.
Price, J. C. (1982). ''Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data.'' *IEEE Trans. on Geoscience and Remote Sensing*, 20, 286–292.
Quinn, P., Beven, K., Chevallier, P., and Planchon, O. (1991). ''The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models.'' *Hydrological Processes*, 5(1), 59–79.
Rango, A., Salomonson, V. V., and Foster, J. L. (1975). ''Employment of satellite snow cover observations for improving seasonal runoff estimate.'' *Operational applications of satellite snow cover observations, NASA SP-391*, NASA, Washington, D.C., 157–174.
Ritchie, J. C. (1995). ''Airborne laser altimeter measurements of landscape topography.'' *Remote Sensing of Environment*, 53(2), 85–90.
Schultz, G. A. (1993). ''Application of GIS and remote sensing in hydrology.'' *Proc., HydroGIS 93: Application of Geographic Information Sys. in Hydr. and Water Resour., IAHS Publ. No. 211*, International Association of Hydrological Sciences, Wallingford, U.K., 127–140.
Schultz, G. A., and Barrett, E. C. (1989). ''Advances in remote sensing for hydrology and water resources management.'' *Tech. Documents in Hydro.*, UNESCO, Paris.
Schultz, G. A., and Engman, E. T. (2000). *Remote sensing in hydrology and water management*, Springer, Berlin.
Seybert, T. A. (1996). ''Effective partitioning of spatial data for use in a distributed runoff model.'' PhD dissertation, Dept. of Civ. and Envir. Engrg., Pennsylvania State University, University Park, Pa.
Shedd, R. C., Peterlin, A., and Fox, L. E. (1992). ''WSR-88D and water management.'' *Proc., Managing Water Resour. during Global Change*, American Water Resources Association, Reno, Nev., 25–31.
Smith, J. A., Baeck, M. L., and Steiner, M. (1996). ''Catastrophic rainfall from and upslope thunderstorm in the central Appalachians: The Rapidan storm of June 27, 1995.'' *Water Resour. Res.*, 32(10), 3099–3113.
Smith, J. A., and Krajewski, W. F. (1993). ''A modeling study of rainfall rate-reflectivity relationships.'' *Water Resour. Res.*, 29(8), 2505–2514.
Snyder, J. P., and Voxland, P. M. (1989). ''An album of map projections.'' *U.S. Geological Survey Profl. Paper 1453*, U.S. Government Printing Office, Washington, D.C.
Steiner, M., Smith, J. A., Burges, S. J., and Alonso, C. V. (1997). ''Use of radar for remote monitoring of rainfall rate and rainfall kinetic energy on a variety of scales.'' Management of landscapes disturbed by channel incision—Stablization, Rehabilitation, Restoration, S. S. Y. Yang, E. J. Langendoen, and F. D. Shields, Jr., eds., University of Mississippi, Oxford, Miss., 831–839.
Tarboton, D. G., Bras, R. L., and Rodrigues-Iturbe, I. (1991). ''On the extraction of channel networks from digital elevation data.'' *Water Resour. Res.*, 5(1), 81–100.
Topographic Science Working Group (TSWG). (1988). ''Topographic science working group report to the land process branch.'' Earth Science and Application Div., NASA Headquarters, Lunar and Planetary Institute, Houston, Tex.
Tribe, A. (1991). ''Automated recognition of valley heads from digital elevation models.'' *Earth Surface Processes and Landforms*, 16(1), 33–49.
Tucker, C. J., Elgies, J. H., McMurtrey, J. L., III, and Fan, C. J. (1979). ''Monitoring corn and soybean crop development with hand-held radiometric spectral data.'' *Remote Sensing Envir.*, 8, 237–248.
U.S. Department of Agriculture (USDA). (1991). ''STATSGO—State soils geographic data base.'' *Miscellaneous Publ. No. 1492*, Nat. Soil Survey Ctr., Natural Resources Conservation Service, Washington, D.C.
U.S. Department of Agriculture (USDA). (1995). ''Soil survey geographic (SSURGO) data base.'' *Miscellaneous Publ. No. 1527*, Nat. Soil Survey Ctr., Natural Resources Conservation Service, Washington, D.C.
U.S. Environmental Protection Agency (USEPA). (1992). ''River Reach File (RF3) update and quality control standards, procedures and management (draft).'' Office of Water, Office of Wetlands, Oceans, and Watersheds.
U.S. Environmental Protection Agency (USEPA). (1994). ''The U.S. EPA Reach File version 3.0, Alpha release (RF3-Alpha), technical reference.'' 1st Ed., Washington, D.C.
U.S. Geological Survey (USGS). (1990). *Digital elevation models: data users guide. National mapping program, technical instructions, data users guide 5*, Department of the Interior, Reston, Va.
U.S. Geological Survey (USGS). (1992). ''US GeoData.'' Brochure, Reston, Va.
U.S. Geological Survey (USGS). (1993). US GeoData digital line graphs.'' Factsheet, Reston, Va.
Wilson, J. W., and Brandes, E. A. (1979). ''Radar measurement of rainfall —A summary.'' *Bull. Am. Meteorol. Soc.*, 60(9), 1048–1058.
Wolock, D. M., and Price, C. V. (1994). ''Effects of digital elevation map scale and data resolution on a topographically-based watershed model.'' *Water Resour. Res.*, 30(11), 3041–3052.
Zawadzki, I. (1982). ''The quantitative interpretation of weather radar measurements.'' *Atmos. Oc.*, 20, 158–180.
Zawadzki, I. (1984). ''Factors affecting the precision of radar measurements of rain.'' *Proc., 22nd Conf. on Radar Meteorology*, American Meteor. Society, Boston.
Zebker, H. A., and Goldstein, R. M. (1986). ''Topographic mapping from interferometric SAR observations.'' *J. Geophys. Res.*, 91, 4993–4999.
Zevenbergen, L. W., and Thorne, C. R. (1987). ''Quantitative analysis of land surface topography.'' *Earth Surface Processes Landforms*, 12(1), 47–56.
Zhang, W., Montgomery, D. R. (1994). ''Digital elevation model grid size, landscape representation, and hydrologic simulations.'' *Water Resour. Res.*, 30(4), 1019–1028.