Hydrologic *and* Hydraulic

Modeling Support

with Geographic Information Systems

Compiled and edited by Dr. David Maidment and Dr. Dean Djokic

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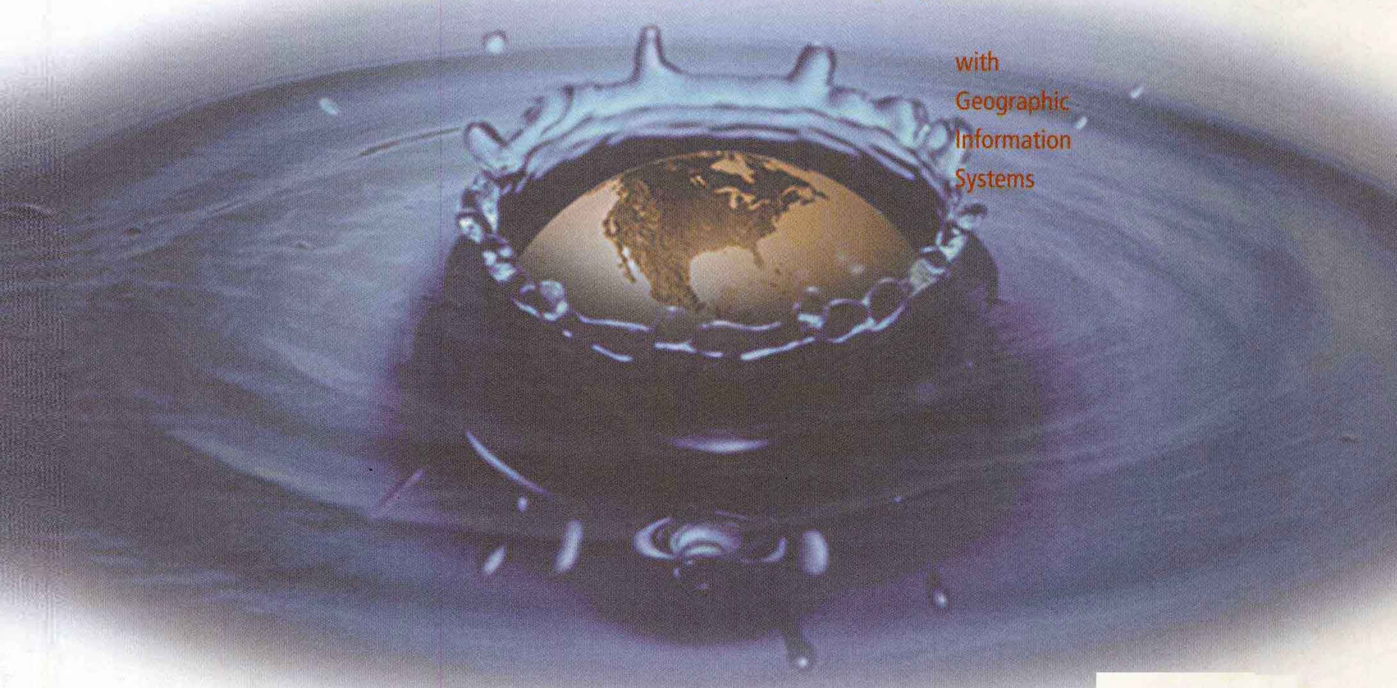

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Introduction

BACKGROUND

THIS BOOK is a compilation of the invited papers in the Water Resources track at the 1999 ESRI® International User Conference held in San Diego from July 26 through July 30, 1999. The idea behind the invited papers and sessions was to produce a high-quality forum for dealing with specific GIS issues in water resources. It was intended that the results of these sessions would define the state of the art for that particular topic and serve as a reference for the larger community interested in GIS applications in water resources.

The specific topics presented in this book deal with terrain modeling and GIS support for hydrologic and hydraulic modeling, with a focus on NexGen models developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers. Although the focus is on HEC model support, the GIS principles presented here apply to most water resources models.

The technology and methods for GIS support of water resources applications (with a focus on water resources modeling) have been available for many years as indicated by the extensive bibliography in the field. There are several reasons why the available technology has not been more widely used in day-to-day water resources operations:

- Suitable data has been lacking.
- The expense of GIS technology has limited its use to larger organizations, while most of the services in the field are in the domain of small consulting companies.
- The engineering community has not been educated enough in GIS, while the GIS community has not being educated enough in engineering fields, making cross-discipline communication and implementation difficult.

These barriers are being brought down quickly. The development of national hydrographic and elevation data sets, and new techniques for elevation derivation that are feasible and accurate, make core data much easier to obtain. Advanced desktop GIS software and the lower cost of required hardware make GIS functionality available to smaller organizations. Finally, the development of well-established data-processing procedures and packaged GIS solutions for specific water resources tasks (including education and training) make GIS implementation much simpler and less threatening to traditionally non-GIS organizations.

The invited papers and subsequently this book have a role in this confluence of events. The intent is to provide in one place the overview of the GIS technology, methods, issues, and tools that are established and can be used by water resources practitioners to put GIS technology to quick, practical, and efficient use in the area of hydrologic and hydraulic modeling. It also provides to the GIS community an overview of GIS applications and issues that the water resources community is interested in.

CONTENT

The book contains three main sections. The papers within each section are designed so that the first presents the basic principles, the next describes available tools and techniques, and the final paper(s) presents practical application of the GIS tools and techniques to real-world modeling projects.

The first section deals with the use of digital elevation models (DEMs) in water resources modeling. It provides the foundation for understanding the role and impact of DEMs in modeling support. In "Digital Elevation Model Issues in Water Resources Modeling," Garbrecht and Martz present capabilities and limitations of DEMs in water resources modeling support. They address issues of data availability, quality, and resolution, as well as capabilities and limitations in automated extraction of topographic parameters from DEMs.

In "Preparation of DEMs for Use in Environmental Modeling Analysis," Saunders discusses techniques for manipulating DEMs by integrating vector hydrography to obtain the hydrologically correct terrain representation and best results for DEM-derived output. Perez, in "Source Water Protection Project: A Comparison of Watershed Delineation Methods in ARC/INFO and ArcView GIS," presents the efforts by the Washington State DOT to use DEM and GIS techniques to delineate the Source Water Protection Areas (contributing watershed area) for all surface water intakes statewide.

The second section presents the issues of rainfall-runoff modeling using GIS and HEC-HMS. The Hydrologic Modeling System (HMS), developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers, is one of the most popular computer models for simulation of precipitation-runoff processes. "DEM Preprocessing for Efficient Watershed Delineation" by Djokic and Ye presents a methodology for DEM preprocessing that facilitates efficient and interactive watershed delineation. This methodology is used as a basis for interactive basin development in GIS tools for HMS model support.

In "GIS Tools for HMS Modeling Support," Olivera and Maidment present a set of raster- and vector-based GIS tools for determination of hydrologic elements and their connectivity, calculation of their parameters, and preparation of an input file for HMS. These tools allow automated model setup that is significantly faster than traditional methods and leads to reproducible results. In "Hydrologic Model of the Buffalo Bayou Using GIS," Doan applies the previously described tools to a watershed that covers most of the Houston metropolitan area. The analysis is based on USGS DEMs at 30-meter cell resolution and stream data from USGS digital line graphs (DLGs) and EPA river reach files (RF1). Physical watershed parameters were extracted using GIS to support hydrologic parameters computation. The model uses grid-based radar (NEXRAD) rainfall in a Standard Hydrologic Grid.

The third and final section of the book deals with the issues related to floodplain modeling using GIS and HEC-RAS. The River Analysis System (RAS), developed by the HEC, is the most popular computer model for simulation of one-dimensional, gradually varied flow in open channels. This section of the book involves a switch from the hydrologic, watershed-based processes and their modeling based on DEM terrain representation described in the previous sections to hydraulic, stream-based processes and their modeling based on triangular irregular network (TIN) terrain representation.

Long, in "Development of Digital Terrain Representation for Use in River Modeling," presents techniques for development of quality TINs that can support RAS modeling. The issues of underwater terrain modeling and inclusion of old cross-section (HEC-2) data are discussed in particular. In "HEC-GeoRAS: Linking GIS to Hydraulic Analysis Using ARC/INFO and HEC-RAS," Ackerman, Evans, and

Brunner present GIS tools developed at HEC to support RAS modeling. These tools speed up spatial data pre- and postprocessing and allow the engineer to concentrate on hydraulic principles during model development and analysis, rather than focusing on applying the GIS.

In "Floodplain Determination Using ArcView GIS and HEC-RAS," Kraus presents the application of GIS tools for RAS modeling support on a floodplain study for the National Flood Insurance Program. Cross sections were located to coincide with field-surveyed cross sections of the channels. The extracted data was imported into HEC-RAS and combined with the field-surveyed data to construct full floodplain cross sections. HEC-RAS-computed water surface elevations along the channels were transferred to ArcView® GIS where the floodplain limits were automatically determined. Dodson and Li, in "The Accuracy and Efficiency of GIS-Based Floodplain Determinations," compare the accuracy and efficiency of computing floodplain elevations and mapping floodplain boundaries using the traditional and the GIS approach.

This book presents the most up-to-date survey presently available of the application of GIS to flood hydrology and hydraulics. Its primary focus is on the use of grids or triangulated irregular networks to describe the watershed and stream channel terrain surfaces. It demonstrates that the techniques in this field have evolved into a sound, reliable technological base, which can be used with confidence to construct hydrologic and hydraulic models based on GIS data.

What further innovations can be expected in this field in the near future? One of the key GIS data structures having potential for application in the water resources field is the network model. The river network is the backbone structure for describing the motion of water through the landscape. It connects watersheds with their stream channels, describes the connectivity of points along rivers, and determines the ordering of flow as it passes from one river reach to the next. Up to this point, the GIS network model has been mainly applied to transportation problems involving routing vehicles from one location to another on a street system.

With the advent of the new geodatabase concepts in ArcInfo™ 8, which will also later be incorporated into ArcView GIS, the network model will be able to be incorporated much more directly into water resource modeling than has been the case. This innovation in software is enhanced by the fact that the National Hydrography

Dataset has recently been released by the USGS and EPA, providing a comprehensive description at 1:100,000 scale of the river network of the United States. The combination of raster data, grids, and TINs, as described in this book, along with a stronger network approach, will enhance the capability to connect multiple hydrologic and hydraulic models to a common geodatabase of a region.

The design of a geodatabase for water resource applications, called the Arc Hydrology Data Model, is presently being carried out by a GIS in Water Resources Consortium formed by the Center for Research in Water Resources (CRWR) of the University of Texas at Austin, by ESRI, and by representatives of government agencies, consulting firms, and academic institutions. Further information about this effort can be found at www.crwr.utexas.edu/giswr. The goals of this effort are to support mapping of water features, linear referencing of locations along a river network, and dynamic modeling of water resources. The core Arc Hydrology Data Model will provide a foundation for extension and customization to fit the needs of particular organizations and physical settings. This data model is being built using the object representation structure of ArcInfo 8, which will yield new opportunities for the closer synthesis of GIS and hydrology.

While the new geodatabase concepts will take time to develop, the key ideas presented in this book will remain valid and will be incorporated in the new software systems. The editors of this book have been involved in GIS hydrology for more than a decade. From this perspective, we have seen the growth of this field from a few individuals working in research institutions to a mature community of GIS and hydrology professionals dedicated to the common goal of putting hydrologic analysis on a more secure footing of geospatial data and software engineering techniques. Progress in this field depends on many factors, including data development, software innovations, research insights, educational programs, and most of all, the dedication of the people involved in the GIS hydrology community. The publication of this book is a milestone along the journey of development of this field. We hope that you will find it useful and informative.

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Contents

Paper 1

Digital Elevation Model Issues in Water Resources Modeling

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ABSTRACT

TOPOGRAPHY plays an important role in the distribution and flux of water and energy within natural landscapes. The automated extraction of topographic parameters from DEMs is recognized as a viable alternative to traditional surveys and manual evaluation of topographic maps, particularly as the quality and coverage of DEM data increase. The capabilities and limitations of DEMs for use in water resources model applications are reviewed. Specifically, data availability, quality, and resolution are discussed from an application perspective. Issues related to the automated extraction of topographic and drainage information from DEMs are presented. These include the identification of drainage in the presence of pits and flat areas in the DEM, the determining role of channel source definition in drainage network configuration, and network analysis capabilities for raster networks. Also presented are the latest research results regarding the reduction of distributed subcatchment properties into a representative value for the subcatchments. Increasing quality and resolution of DEM products, new raster-processing methodologies, and expanding GIS capabilities and linkages with water resources models are expected to lead to a heavier reliance on DEMs as a source of topographic and surface drainage information.

INTRODUCTION

Hydrologic process and water resource issues are commonly investigated by use of distributed watershed models. These watershed models require physiographic information such as configuration of the channel network, location of drainage divides, channel length and slope, and subcatchment geometric properties. Traditionally, these parameters are obtained from maps or field surveys. Over the last two decades this information has been increasingly derived directly from digital representations of the topography (Jenson and Domingue, 1988; Mark, 1984; Moore et al., 1991; Martz and Garbrecht, 1992). The digital representation of the topography is called a digital elevation model (DEM). The automated derivation of topographic watershed data from DEMs is faster, less subjective, and provides more reproducible measurements than traditional manual techniques applied to topographic maps (Tribe, 1992). Digital data generated by this approach also have the advantage of being readily imported and analyzed by geographic information systems (GIS). The technological advances provided by GIS and the increasing availability and quality of DEMs have greatly expanded the application potential of DEMs to many hydrologic, hydraulic, water resources, and environmental investigations (Moore et al., 1991). In this paper the production, availability, quality, resolution, and capabilities of DEMs are reviewed and discussed with respect to the derivation of topographic data in support of hydrologic and water resources investigations. This paper covers DEMs of natural landscapes only and does not extend to urbanized settings where small-scale and manmade structures such as street gutters, inlets, drainage ditches, and culverts control surface drainage patterns.

DEM PRODUCTION, QUALITY, AND AVAILABILITY

The most common DEM data structure is the raster or grid structure. This normally consists of a matrix of square grid cells with the mean cell elevation stored in a two-dimensional array. Location of a cell in geographic space is implicit from the row and column location of the cell within the array, provided that the boundary coordinates (georeferences) of the array are known. Grid DEMs are widely available and used because of their simplicity, processing ease, and computational efficiency (Martz and Garbrecht, 1992). Disadvantages include grid size dependency of certain computed topographic parameters (Fairfield and Leymarie, 1991) and inability to locally adjust the grid size to the dimensions of topographic land surface features. Other DEM data structures, such as the triangulated irregular network and contour-based structures, have overcome some of the disadvantages of grid DEMs. However, they have shortcomings of their own and are not as widely available and used as grid DEMs. The remainder of this paper will focus on the popular grid-type DEMs.

In the United States, the most widely available DEMs are those distributed by the U.S. Geological Survey (USGS). They are produced using elevation data derived from existing contour maps, digitized elevations, and photogrammetric stereomodels based on aerial photographs and satellite remote-sensing images. The USGS 7.5-minute DEMs have a grid spacing of 30 by 30 meters and are based on the Universal Transverse Mercator (UTM) georeferencing system. These DEMs provide coverage in 7.5-by-7.5-minute blocks, and each block provides the same coverage as a standard USGS 7.5-minute map series quadrangle (USGS, 1990). The USGS 1-degree DEMs have a grid spacing of 3 by 3 arc-seconds and provide coverage in 1-by-1-degree blocks. Two coverages provide the same coverage as a standard USGS 1-by-2-degree map series quadrangle. The USGS 30-minute DEMs have a grid spacing of 2 by 2 arc-seconds and consist of four 15-by-15-minute DEM blocks. Two 30-minute DEMs provide the same coverage as a standard USGS 30-by-60-minute map series quadrangle. All USGS DEMs provide elevation values in integer feet or meters.

DEMs produced by the USGS are classified into three levels of increasing quality. Level 1 classification is generally reserved for data derived from scanning National High-Altitude Photography Program, National Aerial Photography Program, or equivalent photography. A vertical Root Mean Square Error (RMSE) of 7 meters is the targeted accuracy standard, and a RMSE of 15 meters is the maximum permitted. Level 2 classification is for elevation data sets that have been processed or smoothed for consistency and edited to remove identifiable systematic errors. A RMSE of one-half of the original map contour interval is the maximum permitted. There are no errors greater than one contour interval in magnitude. Level 3 classification DEMs are derived from digital line graph (DLG) data by using selected elements from both hypsography (contours, spot elevations) and hydrography (lakes, shorelines, drainage). If necessary, ridgelines and major transportation features are also included in the derivation. A RMSE of one-third of the contour interval is the maximum permitted. There are no errors greater than two-thirds of the contour interval in magnitude. Most data produced within the last decade fall into the level 2 classification. The availability of level 3 DEMs is very limited.

The USGS, Earth Science Information Center, Reston, Virginia, offers a variety of digital elevation data products (USGS, 1990). Other sources for DEM data include the former Defense Mapping Agency (DMA) (now the National Imagery and Mapping Agency, NIMA), and the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA). Custom DEM data can also be obtained through a number of commercial providers. New technologies, such as Laser Altimetry (LA) (Ritchie, 1995) and Radar Interferometry (RI) (Zebker and Goldstein, 1986), are currently being explored for production of high-quality and high-resolution global DEMs (Gesch, 1994).

DEM ACCURACY CONSIDERATIONS IN WATER RESOURCE APPLICATIONS

DEMs are used in water resources projects to identify drainage features such as ridges, valley bottoms, channel networks, and surface drainage patterns, and to quantify subcatchment and channel properties such as size, length, and slope. The accuracy of this topographic information is a function both of the quality and resolution of the DEM, and of the DEM processing algorithms used to extract this information.

The suitability of a USGS DEM for water resources projects depends largely on the DEM production techniques. USGS 7.5-minute DEMs produced before 1988 were mainly based on manual profiling of photogrammetric stereomodels (USGS, 1990). In low-relief landscapes, the resulting DEMs often display systematic east–west striping patterns that can make them unsuitable for parameterization of drainage features (Garbrecht and Starks, 1995). Figure 1a shows two adjacent DEMs that were produced by different techniques. The left side illustrates the east–west striping pattern associated with the manual profiling of photogrammetric stereomodels.

The impact of the striping on drainage studies is threefold. First, the outlines of drainage features, such as depressions or drainage paths, are not well defined. Boundaries of shallow features that have a north-to-south orientation (i.e., perpendicular to the striping) are often represented in the DEM as ragged lines having east-to-west indentations. Second, drainage paths are systematically biased in the

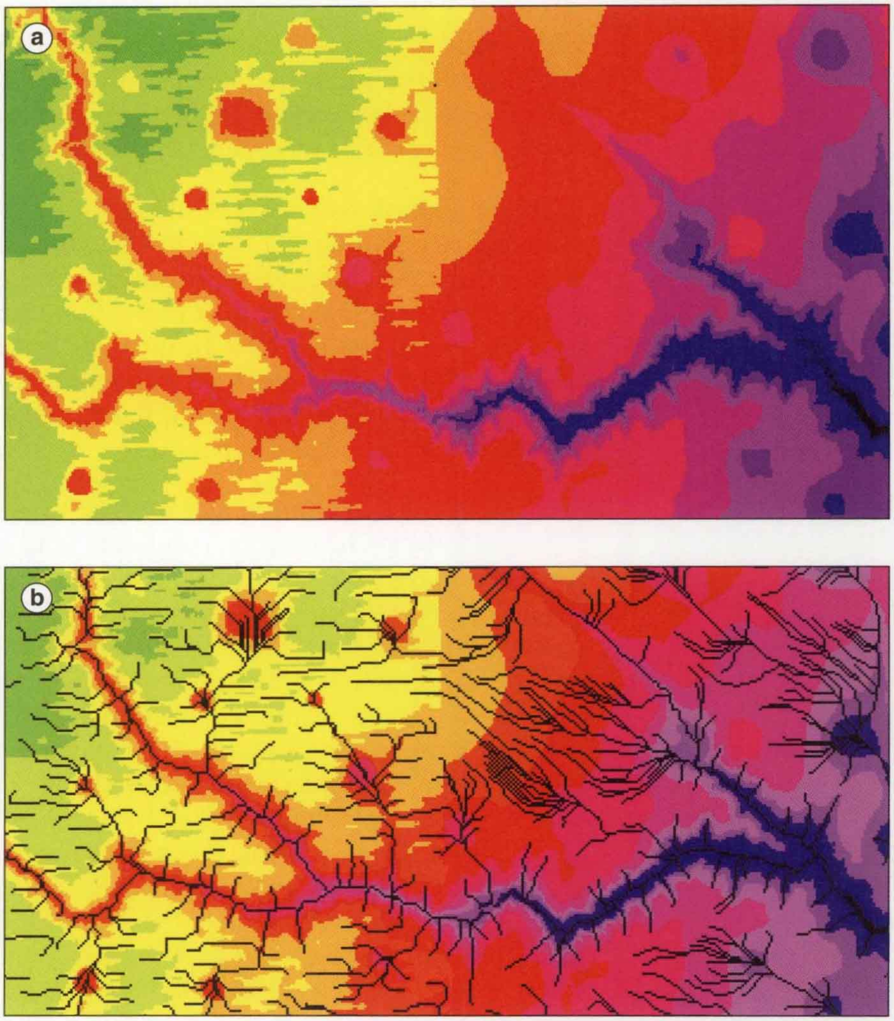

Figure 1. Coverage of two adjacent USGS 7.5-minute DEMs near Amarillo, Texas; (a) DEM elevation values; (b) GIS-derived drainage network.

east-to-west direction because of flow draining into and following the artificial elevation stripes. Figure 1b illustrates the differences in drainage pattern as a result of the striping pattern in the elevation data. And, third, the striping may introduce drainage blockages in the north-to-south flow component. These drainage blockages can produce artificial depressions of varying sizes. The source of the striping is a combination of human and algorithmic errors associated with the manual profiling method (B. Kunert, USGS, Rolla, Mid Continent Mapping Center, personal communication). While these "striping" errors are well recognized (Garbrecht and Starks, 1995), they are within the accuracy standards of the USGS (1990). While most DEMs being developed today are derived from DLGs and are processed to level 2 standards, many DEMs being distributed today were developed in the past and meet only level 1 standards.

Level 1 standards demand a RMSE value of 7 meters, with a maximum permitted value of 15 meters. An absolute elevation error tolerance of 50 meters is set for blunders for any grid node when compared to the true height from mean sea level. Also, any array of 49 contiguous elevation points shall not be in error by more than 21 meters (USGS, 1990). These tolerances in elevation are large for drainage investigations since an elevation difference of 1 or 2 meters can affect flow path and runoff characteristics.

DEM horizontal resolution and its ratio to vertical resolution can have a significant bearing on computed land surface parameters that involve differences in elevations. For example, slope is computed as the difference in elevation between two adjacent pixels divided by the distance between them. Since DEM elevations are generally reported in full meters or feet, the computed slope can only take on a limited number of discreet values. For a 30-meter DEM with elevations reported in meters, a slope value between two pixels can be zero (no change in elevation), 0.033 (1-meter change in elevation), or a multiple thereof. Such increments may be adequate to represent slope values in mountainous terrain, but for flat areas, such as the Great Plains of the United States, a 1-meter vertical DEM resolution is insufficient to provide accurate local slope values. Thus, DEMs of low-relief landscape and limited vertical resolution do not lend themselves well to an accurate determination of drainage slopes and precise location of channels and ridges.

The problems of DEM quality and resolution can generally not be overcome by smoothing or averaging the DEM. Such approaches simply cover up the problems without increasing the quality of the output. The easiest solution to overcome the described resolution problems is to custom produce a DEM with a prespecified horizontal-to-vertical resolution ratio, or to use a high-resolution DEM produced by more advanced methods. Other solutions include the use of DEM analysis methods that are designed to overcome problems associated with digital representations of low-relief landscapes by DEMs of limited resolution (Garbrecht and Martz, 1999a). Examples of such problems are the increased occurrence and size of flat areas and spurious pits. Pits are cells that have no adjacent cell at a lower elevation and, consequently, have no downslope flow path to an adjacent cell. On the other hand, flat areas are characterized by adjacent cells with the same elevation values. Pits and flat areas occur in most raster DEMs, but are predominant in limited-resolution DEMs of low-relief landscapes. Figure 2 shows the spatial distribution and extent of pits and flat areas (areas in green) of a DEM of a watershed in central Oklahoma. The predominance of pits and flat areas in the valley bottoms (low-relief areas) are clearly visible. Pits are usually viewed as spurious features that arise from interpolation errors during DEM generation and truncation of interpolated values on output (O'Callaghan and Mark, 1984; Mark, 1988; Fairfield and Leymarie, 1991). Pits are a major difficulty for DEM evaluation methods that rely on the overland flow simulation approach to drainage analysis because a lack of downslope flow paths leads to incomplete drainage pattern definition. The drainage identification problems for flat areas are similar to those encountered for pits. This subject is addressed in greater depth in the section on automated extraction of drainage features from DEMs.

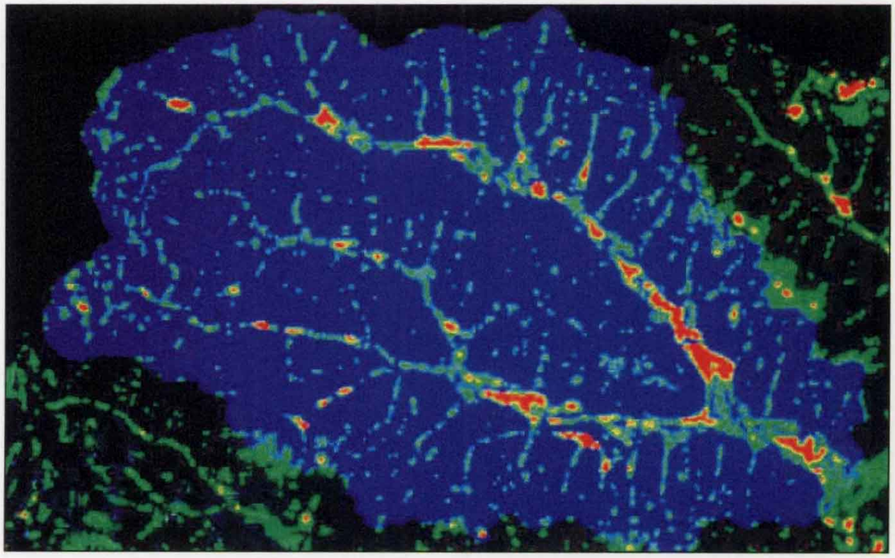

Figure 2. Spatial distribution and extent of pits and flat areas in a DEM of a watershed in central Oklahoma.

DEM SELECTION CRITERIA

Both quality and resolution must be considered in selecting a DEM for hydrologic modeling. Quality refers to the accuracy of the elevation data, while resolution refers to the precision of the data, specifically to the horizontal grid spacing and vertical elevation incrementation. 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-by-30-meter DEM data (levels 1 and 2) has broad accuracy standards and a rather coarse resolution with documented shortcomings (Garbrecht and Starks, 1995; Ostman, 1987; Topographic Science Working Group, 1988). 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 underway to assess the impact of accuracy limitations, noise, and low resolution of DEM data on modeling results. Examples of such studies include Wolock and Price (1994) and Zhang and Montgomery (1994).

The accuracy of drainage features extracted from DEMs as a function of DEM resolution was investigated by Garbrecht and Martz (1994). The horizontal resolution of a DEM with an original grid spacing of 30 meters was decreased by cell aggregation. Selected drainage features for several hypothetical channel network configurations were extracted for a range of DEM resolutions using the TOPAZ software (Garbrecht and Martz, 1994). Figure 3 illustrates the loss of accuracy from left to right with increasing grid coefficient. The grid coefficient is the area of a cell divided by the network reference area, which is the mean subcatchment area. The values shown are for selected network features such as channel source area, number of channels, channel length, and drainage density. The sensitivity analysis suggested that a DEM should have a grid area of less than 5 percent of the network reference area to reproduce the selected drainage features with an accuracy of about 10 percent. It was concluded that the grid resolution dependency was introduced by the inability of a DEM to accurately reproduce drainage features that are at the same scale as the spatial resolution of the DEM. For sinuous channels, this results in shorter channel lengths, and for networks with high drainage density, it leads to channel and drainage area capturing. Channel and drainage area capturing occurs when the DEM resolution can no longer resolve the separation between channels or drainage boundaries. In such situations, the number of channels, the size of direct drainage areas, and the channel network