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Emerging Tools and Technologies in Watershed Management

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Abstract.—The field of watershed management is highly dependent on spatially distributed data. Over the past decade, significant advances have been made toward the capture, storage, and use of spatial data. Emerging tools and technologies hold great promise for improving the scientific understanding of watershed processes and are already revolutionizing watershed research. Issues of scale, error, and uncertainty are highly relevant to understanding surface processes and are intimately tied to these emerging tools. This paper provides a summary of some of the ways in which global positioning systems, geographic information systems, remote sensing and distributed models are being integrated to provide information to the scientific and management communities

Introduction

One of the underlying principles of watershed management is the recognition of the interrelationships among land use, soil, and water, and the linkages between uplands and downstream areas (Brooks et al. 1997). Watershed management has always required synthesizing a vast array of spatial information to assess downstream impacts. Moreover, it is important to know not only the percent of a given land use, but also its distribution in a watershed. For example, runoff and sediment from a dirt road has a greater probability of reaching a stream channel if the road is located in a floodplain rather than on a ridge top.

In the past, obtaining spatial information has been time consuming and difficult. As a result, many of our watershed assessment methods and are predicated on only general information regarding the spatial characteristics of our watersheds. A good example of such an approach is the SCS Curve Number Runoff Model (Haan et al. 1994), a lumped parameter model, necessitating only the percentage of different land use types that occur on each soil type for parameterization (i.e. selecting the curve number). However, even the relatively simple task of manually overlaying land use and soil maps, delineating the watershed and soil/land use boundaries, and then finding their with a planimeter could take a watershed manager days, if not weeks, to accomplish for a complex watershed. Using conventional means, the time it takes to perform such analyses at regular intervals to assess the effects of dynamic land use is prohibitive.

The revolution currently occurring in the field of information technology is changing the profession of watershed management. New tools such as global positioning systems (GPS) and remote sensing are being developed to inventory and monitor watershed characteristics. Geographic information systems (GIS) have the power to collect, store, analyze and display georeferenced information. Maps have always been one of the principal tools of a watershed manager and these computerized maps are becoming one of the most important tools in watershed management (NRC 1999; Goodchild et al. 1993; Franklin 1994). In turn, GIS are being linked to simulation models and decision support systems. This change is fueled by rapid expansion in the computer industry that is providing technology capable of delivering, storing, and analyzing vast quantities of information.

In theory, given a suite of sophisticated research tools, solving the aforementioned Curve Number problem should now be simple and quick. Unfortunately, that is usually not the case. The spatial (GIS) data for soils and land use first must be gathered and entered into the computer, models redesigned and encoded to efficiently use the new information, and watershed managers trained to use the new technology. This investment in developing new processes is essentially an up-front cost that will diminish and pay large dividends as techniques are developed and improved.

The profession of watershed management has already embarked on this process. Databases are being developed (Lytle et al. 1996) and spatial data is becoming readily available through the Internet (NRC 1999, Appendix B). Models and decision support systems (DSS) that can utilize the spatial information are becoming available at a rapid rate (NRC 1999; Corwin et al. 1999; Poiani and Bedford 1995). Universities are starting to offer advanced courses and workshops on GIS

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applications for hydrology and watershed management (Miller and Guertin 1999). Increasingly, young professionals have knowledge and experience that will accelerate the process of utilizing these emerging tools and technologies.

The goal of this paper is to review the status of emerging information technologies in relation to their contributions to watershed management. Special emphasis will be paid to GIS, which is becoming a key component to many of the new tools being developed. An attempt will be made to identify research needs to advance not only technological development, but also the wise use of these powerful tools.

Information Technology and the Decision Making Process

The art and science of planning and decision making has always involved the gathering, analysis and synthesis of raw data to derive information to assist decision makers. While new technologies are improving this process, the basic objectives remain the same. The steps in the process incorporating the use of the new technologies in watershed management are illustrated in figure 1.

The first step remains data acquisition of spatial and non-spatial data and the creation of a database to support later activities. New tools such GPS, remote sensing, and real-time telemetry have augmented traditional surveying and inventory methods. GIS are increasingly being used to store both georeferenced data and associated attribution information and can be linked to relational databases, thereby improving the ability to store and access large data sets.

The importance of GIS in for inventorying and monitoring was identified by Franklin (1994). For example, GIS can provide a "snapshot" in time of a watershed or landscape features. By updating the GIS database through time changes can be observed, studied and quantified. GIS not only have the capability to capture and store georeferenced data but can also be used as analysis tools (Burrough and McDonnell 1998). Secondary data layers can be created through spatial analysis, and the raw and secondary layers then synthesized through the use of a model to create products useful to land managers. Modeling can either be done within GIS (Tomlin 1990) or the GIS can provide data to parameterize an external model. Likewise, information can be used directly in a GIS to support decision making (Guertin et al. 1998) or model results entered into a decision support tool or optimization package (Johnson 1992; Lane et al. 1991, Lawrence et al. 1997).

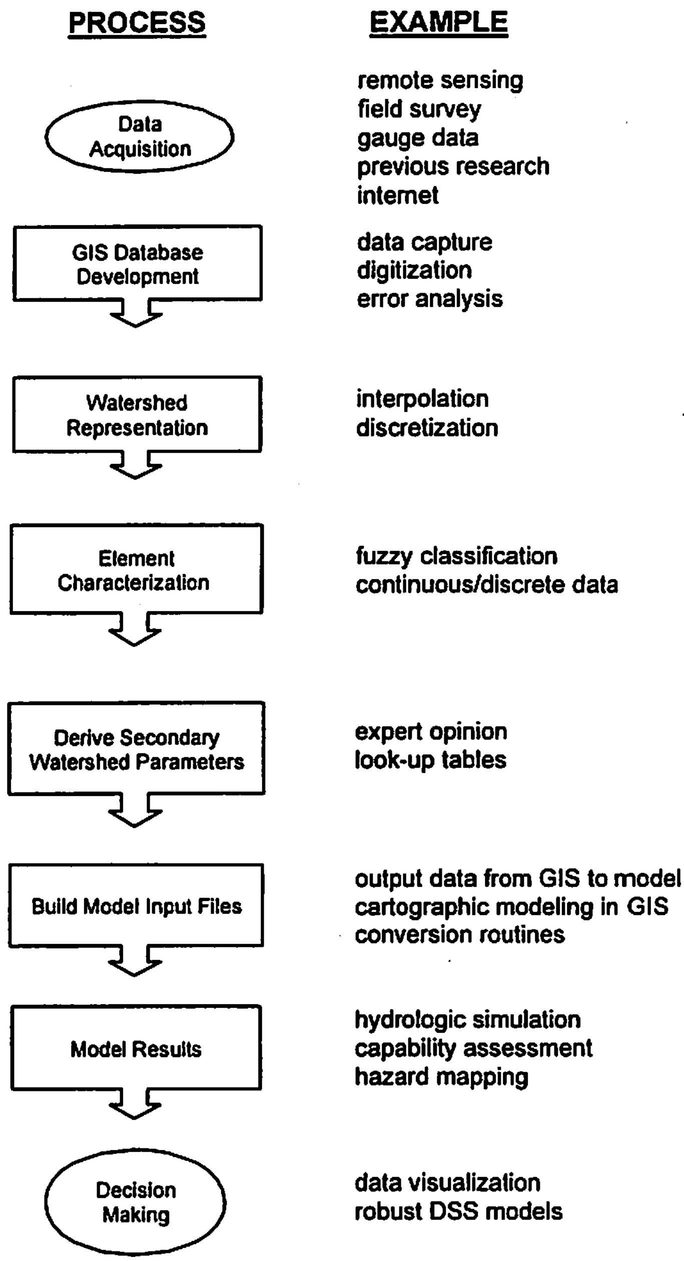

Figure 1. Schematic illustrating the use of emerging tools and technology in watershed management.

Data Acquisition

By definition, watershed and landscape processes are spatially distributed, and a host of surface characteristics dictate hydrological responses to landscape change. Assessment and modeling techniques must therefore account for the spatial variability of important variables, including soil, vegetation, management, topographic, geologic, and hydrologic characteristics. Determining the precise boundaries of these and other characteristics is critical, yet a daunting proposition. Mapping techniques relying on surface travel and surveying equipment are tedious, locally intensive but non-continuous, and relatively inaccurate. Advances in the spatial characterization of the earth, specifically the advent of remote sensing and global positioning systems (GPS), allow for the rapid and precise assessment and mapping of spatially distributed surface properties.

Global Positioning Systems

Since the late 1970's GPS satellites have been launched which are designed and operated by the US Department of Defense (DOD) and recently private corporations and foreign governments have been making GPS signal data available (US Coast Guard 1999). In 1995 a full constellation providing global coverage was achieved by the DOD. This configuration provides continuous coverage with a minimum of four visible satellites to any point on Earth (Twigg 1998). GPS satellite orbits are well known, and their positions highly predictable through time. These satellites broadcast two radio signals (L1 and L2) which carry navigation codes and messages. Ground sensors, which are freely available and may be purchased for less than $200, receive the signals. The codes and messages are used by the unit to calculate distances among the satellites, and geometric algorithms are employed to determine the precise position of the receiver.

While each satellite broadcasts signals accessible by any GPS unit, the DOD adjusts the signal for security purposes. This process of adjusting the signal, known as selective availability (SA) reduces the accuracy of any GPS position that does not contain an anti-SA encryption chip to less than 100m in the horizontal and less than 150m in the vertical directions. The L1 signal provides a precise position code to receivers containing encryption chips to provide accuracy to less than 15m. Receivers that are incapable of interpreting the L1 signal rely on the L2 signal, and must employ differential GPS techniques to improve the positional accuracy (US Navy 1999).

The advantages held by GPS over traditional field survey techniques for watershed management are many and its potential in hydrology and watershed management profound. Some examples of how GPS technology is advancing field surveying: navigation to research sites is made easier; accurate positioning of important positions is direct; the boundaries of spatially distributed characteristics can be traced. Field hydrologists can use a GPS to fix the location of observation points, such as channel cross section, precipitation gauges, weather stations, flumes, soil plots, observation wells, and vegetation plots. GPS are being employed in such diverse fields as precision agriculture, topographic mapping, and bathymetric surveying (Clark and Lee 1998; Wilson et al. 1998; Yang et al. 1997). For example, Guay et al. (1999) used GPS coupled with sonar to map the bathymetry of Topock Marsh in Arizona much faster that traditional surveying techniques. It should be recognized that the use of GPS is limited in its ability to fully spatially characterize an area. It is most useful for point and boundary surveys, and other tools must be employed on large areas or where fully distributed information is required.

Remote Sensing

For the purposes of this paper, we will use Schott's (1997) definition of remote sensing, as the field of study associated with extracting information about an object without coming into contact with it. While broad, this definition reinforces the notion that data can be attained without physical inspection and allows for large-scale synaptic research linking ground and remotely based observations. We will make a further distinction and only focus on remote sensing of the electromagnetic spectrum (EM) in this discussion, thus obviating magnetic, sound, and nuclear waves. Two types of EM sensing are employed in landscape studies: optical, which focuses on short wavelength from the ultraviolet to the long-wave infrared spectra; and radar, which uses the microwave (long wavelength) portion of the EM spectrum (figure 2). Many types of imaging, including vision, photography (both ground- and aerial-based), satellite observation, radar, sonar, and astronomy are classified as remote sensing, and these techniques are widely applied in earth science observation, landscape characterization, modeling, and management. An emerging field, remote sensing is expanding rapidly in consort with advanced computing and engineering technologies.

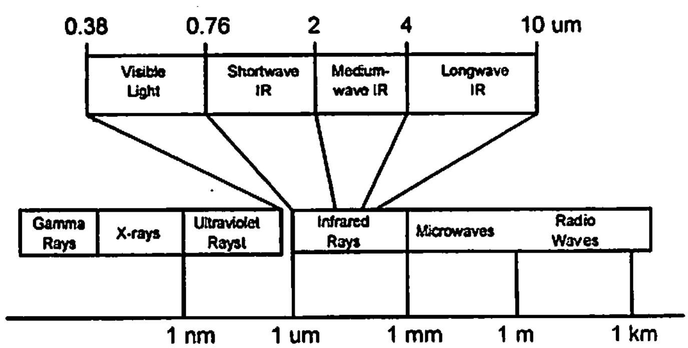

Figure 2. The electromagnetic spectrum.

Optical

Optical remote sensing, as stated earlier, utilizes the shorter wavelength rays of the EM spectrum. Energy across the EM spectrum is transmitted from the Sun to Earth, where it interacts with the atmosphere and is scattered, reflected, refracted and transmitted before encountering the Earth's surface. Some of the energy is absorbed on the surface, and the remainder is reflected or re-transmitted to the atmosphere. Optical remote sensing instruments are passive devices that record the EM waves as they are emitted from the Earth's surface. Since different land cover combinations interact with the EM field in different ways, it is possible to interpret the signal for landscape characterization purposes.

A host of remote sensing platforms is currently in operation, with many more having served their useable lives and others in production and design phases. Early satellite platforms were limited in the array of sensors deployed, and small windows in the EM spectrum were targeted for specific applications. With improvements in design, engineering materials, and computing power, multi-spectral platforms have been employed that can sense large portions of the EM spectrum, thereby improving classification capabilities. Besides being limited to daylight operation, a significant drawback to optical remote sensing is that it is a passive exercise, highly dependent on atmospheric condition. Clouds or smoke mask surface signals from the sensor, and large areas of the Earth are highly restrictive due to the presence of such atmospheric conditions.

As aptly stated by Schott (1997), traditional surface studies are limited by sample size and because they are point-based. Remote sensing provides a different perspective on the earth, and is suitable for large-scale investigations into surface patterns, trends, and the coordination with ground-based observations for purposes of extrapolation or interpolation. Since different objects, such as soils, geologic material, anthropogenic structures and vegetation affect the EM signal, algorithms can be developed to interpret landscape characteristics (Allen, 1994; Cleland et al. 1994; Lachowski et al., 1998). Many such algorithms have been developed for case-specific applications in vegetation classification, soil analysis, geomorphology, oceanography, and atmospheric sciences (Moran et al. 1994; Wilkinson 1996). A classic example of such an algorithm is the normalized difference vegetation index (NDVI), which uses the spectral ratio between the infrared and red spectra to predict biomass over large areas (Rouse et al., 1973). Advanced image processing tools utilize statistical techniques to classify landscapes into regions of similarity, upon which more specific categorization algorithms may be imposed.

Microwave

As is shown in figure 2, the wavelengths within the microwave spectrum are orders of magnitude longer than those that are sensed in the optical range. Radio Detection And Ranging (RADAR) uses these longer wavelengths to make inferences regarding surface properties for landscape classification. While some RADAR applications are passive, the majority are active systems, wherein a satellite or aircraft emits a microwave signal towards the object of interest and records the signal upon its return. As is the case with optical techniques, RADAR relies on the fact that the object under investigation alters the signal. Algorithms are used to decode the impact of various combinations of surface characteristics on signal behavior.

Synthetic aperture radar (SAR) is an emerging research tool that allows for highly detailed surface mapping through the processing of RADAR signals such that the azimuth resolution is improved in direct proportion to the system aperture size (Henderson and Lewis, 1998). Although the concept of SAR processing was introduced in 1951, advances in the field were held in check by the lack of computers capable of processing the complex signal. The benefits of SAR data are currently hot topics in remote sensing and natural resource research (Henderson and Lewis, 1998; Metternicht and Zinck, 1998; Moran et al 1998).

SAR has great potential for application in natural resource science since it can provide high resolution images, is not affected by atmospheric conditions, is an active system, the return signal is highly affected by the imaged target, the signal can be polarized and is coherent, providing both amplitude and phase as a function of the target. Polarization is useful for landscape, specifically vegetation classification since various land covers alter the polarization to a greater or lesser extent. Inteferometric SAR (IFSAR), wherein a target is sensed multiple times from different positions, can be used to provide highly detailed topographic maps (Lanari et al. 1996; Madsen et al. 1993). Various IFSAR instruments have been used to detect land surface change, flood extent, tree harvesting, ocean currents, sea ice characteristics, and provide digital elevation models (DEMs) superior to and more rapidly than those created by conventional means (Izenberg et al. 1996; Nykanen et al. 1998; Tobita et al. 1998).

Data Delivery

Although the development in GPS and remote sensing has greatly reduced the cost in creating data sets and making information more readily available, the availability of information through the Internet may have more far reaching effects. The University of Arizona has compiled a list of approximately 300 active land-surface hydrology data links (http://www.hwr.arizona.edu / hydro_link.html). Watershed managers can obtain streamflow records (http://h2o.usgs.gov), watershed boundaries (http://water.usgs.gov/public/gis) and digital terrain data (http://nsdi.usgs.gov/nsdi/pages/nsdi004.html) from the U.S. Geological Survey, water quality data, as both maps and numbers, from the EPA's "Surf Your Watershed" site (http://www.epa.gov/surf/), and weather data from the National Climate Data Center (http:/www.ncdc.noaa.gov).

Through the Internet, government agencies and private organizations are now able to make their data and related information available at little or no cost. Even individual watersheds now have their own Web sites, including the Verde River in Arizona (http://www.verde.org) and St. John River in Florida (http://www.riverpage.com). The Internet is allowing access to data, most of it produced by government agencies, to flow freely, and with information being posted on the Web continuously, problems regarding data availability are decreasing steadily.

Spatial Analysis and Modeling

The major obstacles to using GIS to address watershed problems have been the lack of spatial data and computer hardware and software requirements for large data sets. Only a few years ago, using GIS for management applications required creating a new database, a process that could take years. An investment in powerful workstations or main frame computers, which not only had a high initial cost, but additional costs of system support and training, was also necessitated. As such, GIS was the provenance of large government agencies capable of assembling such research facilities. However, with GIS data becoming more readily available and the increased power of desktop personal computers, GIS is becoming available to most hydrologists and watershed managers. Consequently, GIS is emerging as an important tool for watershed management, with tools for spatial analysis and modeling being adapted for its use.

Spatial Analysis

Spatial analysis for hydrology and watershed management has long been an important research field. Many common GIS algorithms were originally developed to address hydrologic applications, such as watershed delineation (Band 1986; Jenson and Dominque 1988) and the computation of flow paths (Quinn et al. 1992). The use of DEMs for watershed characterization has received considerable attention (Beven and Moore 1992). Moore et al. (1992), in their review of terrain modeling, discussed many topographic attributes of hydrologic significance and illustrated their computations. Others have created GIS-based tools for exacting watershed information from DEMs for watershed characterization and model parameterization (Eash 1994; Garbrecht et al. 1996; Miller et al. 1996; Miller et al., 1999). Hutchinson (1989) developed a procedure for gridding elevation that automatically removes spurious pits and incorporates a drainage enforcement algorithm to maintain fidelity with a catchment's drainage network Hutchinson's algorithm has since been incorporated in the GIS software ARC/INFO and many of the watershed characterization procedures are now standard functions in desktop GIS software (ESRI 1996).

Interpolation routines have been developed for GIS applications. Using these techniques, point observations can be interpolated to create spatially distributed coverages across a watershed. Geostatistical techniques are also becoming integrated into GIS, although current GIS-based geostatistics lag behind stand-alone software and GIS is best used to provide input data to these packages. Such approaches, including kriging, multiquadratic, and principle components analysis, are used to interpolate soil information, rainfall, and contaminants (Burrough and McDonnell 1998).

Modeling

In the near future most, if not all, hydrologic models and watershed analysis techniques will utilize GIS. GIS are used to represent the watershed under study for modeling purposes, often through the interpolation of point data (such as rainfall gauge records) and subcatchment definition (figure 1). Once the watershed has been divided into modeling units in this fashion, each element is characterized according to necessary model inputs, and the data input into the specified model. The modeling approaches can be split into two classes. In the first class the model is incorporated entirely within a GIS using cartographic modeling techniques (Tomlin 1990). The products of this approach are usually new GIS coverages containing model results. Land capability or suitability (Sheng et al. 1997), landslide hazard mapping (Carra et al.1991; Montgomery et al. 1997; Montgomery and Dietrich. 1994), and erosion hazard (Warren 1989) are examples of this type of analysis.

Warren (1989) estimated erosion within the GIS using the Universal Soil Loss Equation and used the results to identify areas that need rest or rehabilitation from military training because of severe erosion potential. GIS coverages show areas under stress were created and then used to move military training activities to less impacted areas.

Sheng et al. (1997) developed a procedure for developing countries to classify watersheds and target problem areas so as to more wisely allocate watershed protection funds. In the proposed scheme a watershed is classified as a function of slope, soil erodibility, vegetation cover, rainfall intensity and critical areas. Guertin et al. (1998) developed a GIS-based tool for sustainable livestock management. This tool, RANGEMAP, was developed from grazing allotment management decision-making that address resource production and conservation. The tool was developed using the desktop GIS ARCVIEW GIS 3.1, with the Spatial Analyst extension (ESRI 1996) with a "user-friendly" interface so range conservationists and ranchers can more easily use it. The tool can estimate forage production, utilization rates, stocking rates by pasture, and erosion potential and can be used to determine the effect of different management schemes, such as location of water, grazing systems, and exclusion of riparian areas, on stocking rates and erosion potential. The second class consists of models that are external to the GIS, but use GIS output data for parameterization. Many older and widely used models have already been adapted to link to a GIS for parameterization. Examples include HEC-RAS, an update of HEC-2 (U.S. Army Corps of Engineers 1995), MMS (Leavesley et al. 1996), AGNPS (Young et al. 1989), HUMUS (Wang and Srinivasan 1997), WEPP (Savabi et al., 1995), and BASINS (Lahlou et al. 1996).

Research Needs

Hydrology and watershed management share similar issues with other fields using emerging computer technology: the implementation of distributed computing, improving interoperability of dispersed data sets, the future role of the Internet and legal rights to data. These issues are of secondary importance to scientific advancement, however,, and there are several research areas particularly important to watershed management: those of scale, error analysis, geographic representation, and new model development.

Scale

Scale refers to the resolution at which information is represented and utilized. Information captured and entered into a GIS in raster format is defined by its resolution, while vector-based data is a function of its accuracy. The resolution of the data will have direct effects on analysis results at a range in scales. For example, as a DEM's cell size is increased, local slope estimates decrease (Jensen 1991; Zhang and Montgomery 1994). As a cell increases in size it represents a larger area, hence the averaging of elevations of large areas will result in a smoother, less steep, surface (Wolock and Price 1994). This in turn has an impact on processes such as soil erosion since erosion is directly related to slope.

Miller et al. (1999) found that a high resolution DEMs created using IFSAR provided significantly different results at small scales when compared to other lower resolution DEMs. In this study a range in DEMs was used to generate stream channels for a rangeland watershed using a GIS flow direction algorithm. Figure 3 illustrates the influence of DEM resolution and model type on stream network generation. Note that variability in complexity and number of smaller channels exists among the maps, yet the underlying structure remains constant. Syed (1999) used the same suite of DEMs to parameterize a distributed hydrologic model and found that the choice of DEM significantly altered the results at smaller scales.

Research is needed to address the proper level of complexity, and resolution of spatially distributed data to adequately model and manage watersheds. Different hydrologic processes predominate at different scales, and the level of resolution is largely a function of scale. Small-scale variability in soil properties is important at the plot and hillslope scale since hydrologic processes are highly determined by this factor, but such variability becomes less important at the watershed or basin scale. Furthermore, detailed characterization at larger scales is overly complex and can potentially lead to parameter estimation error in modeling, and hence management. Bloschl and Sivapalan (1995) provide a synopsis of scale issues in hydrology. Both spatial and temporal scaling are dominant factors in watershed management, and GIS together with hydrologic models provides an avenue of research into these subjects.

Error Assessment

As new procedure for integrating GIS-based processes into watershed management are developed and spatial data flows more freely via the Internet, it is important that issues surrounding spatially distributed error and model behavior are addressed. Error can be introduced to the decision-making process at every step illustrated in figure 1. The effects of error have been widely studied in hydrologic modeling through sensitivity analysis, and there is a need for research of this kind to address issues of uncertainty and error in GIS systems.

Thapa and Bessler (1992) provided an overview of sources of error and the authors rightly point to the lure of easy data acquisition as a potential source for unaccounted error. While data availability has improved the ability to

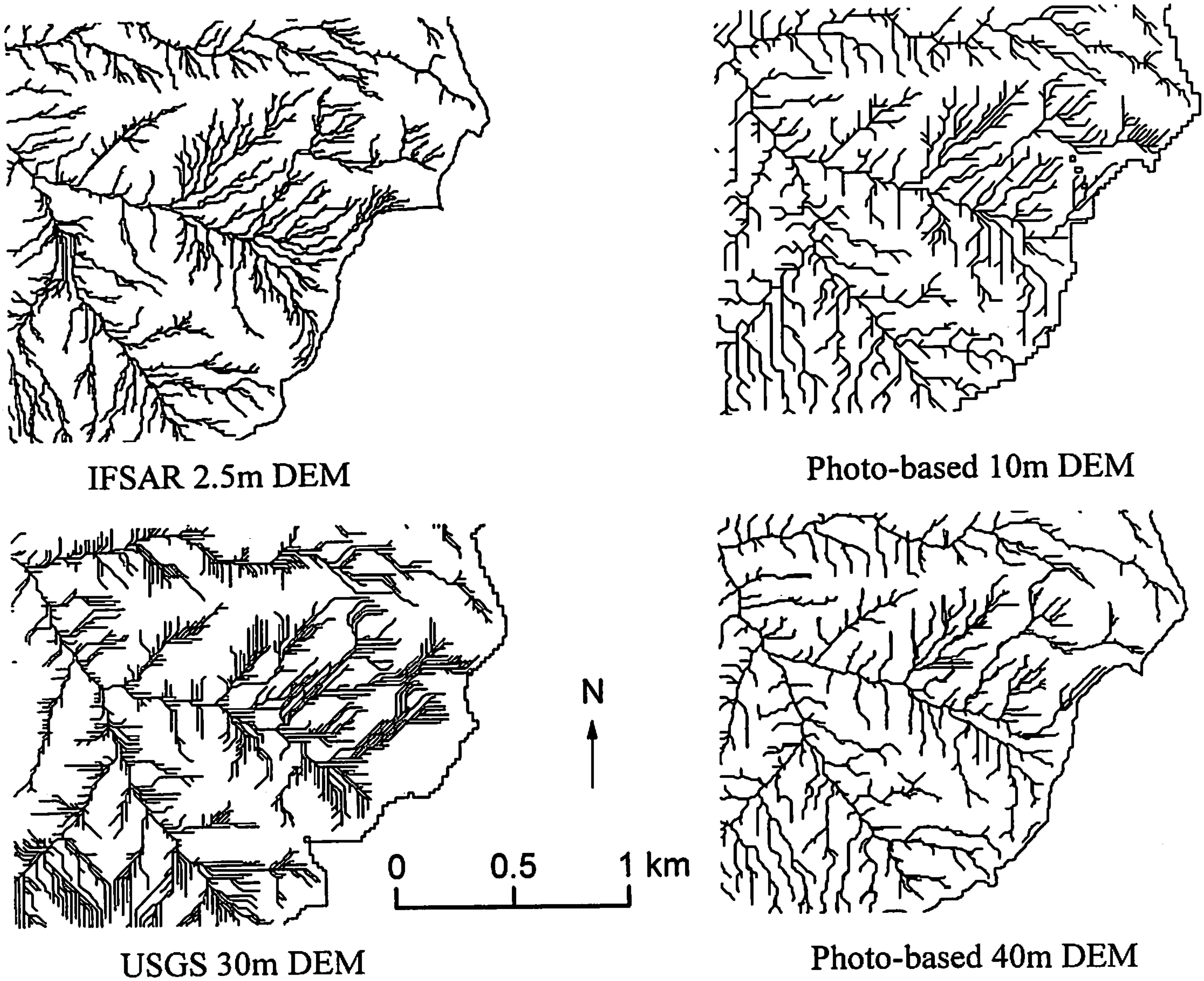

Figure 3. Influence of DEM resolution and type on drainage network representation (from Miller et al., 1999).

quickly develop GIS applications, it is important to quantify problems associated with various techniques (Choudry and Morad 1998; Davis and Keller 1997; Lark and Bolam 1997).

New Model Development

The advent of GIS has altered the prospective for hydrologic modeling substantially. First, the rapid acquisition of spatially variable data allows for the rapid parameterization of models. Second, the potential for providing input to fully distributed models has been greatly enhanced. Physically based models that require extensive data are being developed both within and outside of GIS (Jeton and Smith 1993; Shu-Quiang and Unwin 1992; Srinivasen and Arnold 1994).

This ability to fully describe watershed characteristics at a range of scales provides opportunity for the development of new generations of watershed and basin-scale models. Large area modeling has previously been hindered by the lack of spatial data and by limited computer power. As has been discussed in this paper, both these issues are rapidly disappearing. Arnold et al. (1998) are developing modeling tools for basin assessment using GIS and the basin-scale SWAT model. A statewide system for assessing water quality using GIS tools was presented by Hamlett et al (1992) wherein agricultural practices were modeled for downstream impacts. Raper and Livingstone (1995) argue that the field of geomorphological modeling would be served best by the development of new models that take advantage of object-oriented programming and avoid the geometric limitations of GIS. Walsh (1992) called for the development of spatial decision support systems integrating GIS, expert opinion, and a host of models. The field of spatial modeling is currently undergoing rapid change driven by the emergence of new tools and technologies that facilitate the development and application of cutting-edge models.

Conclusions

In the future, watershed assessments and analysis will primarily be done using GPS, remote sensing, GIS, and related models and tools. This trend will allow watershed managers to quickly and cost effectively address watershed problems in a spatially explicit manner not previously available. However, this advancing technology is not unhindered by concerns (Congalton and Green 1992; Lovejoy 1997). Congalton and Green discussed the problem of being disconnected to the real work when working solely indoors on a computer. Lovejoy questioned the need for "high-tech", relatively expensive GIS-based solutions when "low-tech" solutions may be adequate. A primary function of GIS is the production of computer generated graphics, which are rarely questioned by the public. The graphic capabilities of GIS can lead to misrepresenting the results through the choose of symbols and colors (Monmonier 1996).

Emerging technologies like GPS and GIS hold the promise of making research and management tasks easier and provide capabilities previously unknown. New modeling systems will allow use to ask spatial explicit questions, such as what effect will a buffer have down stream water quality. However, using the new technology does not remove the need of having clear objectives and then determine at what level the new technology will be used.

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