GIS for Watershed Characterization and Modeling

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1 Introduction

As we experience human alterations of the environment during the Anthropocene [1] water is a key resource that is being affected. Enormous ramifications will result in South Africa if Day Zero is reached and Cape Town becomes the first major city to run out of water after an extended drought [2]. According to Postel [3, p. 45], "watersheds function as nature's water factories," so watersheds are critical areas to focus upon to support water resources management.

Since at least the 1930s in the United States watersheds have been considered to provide a sound basis for water resources planning and management [4]. Benjamin Franklin is credited with recognizing the importance of watershed management in 1790, and in China the concept dates to 2000 BC [5]. Watersheds are physiographic areas delineated by drainage divides demarcating the boundaries within which water will flow to a common outlet. Watersheds provide a natural physiographic unit within which to manage water resources for human use and natural ecosystem sustainability. However, watershed boundaries usually do not align with political boundaries, which makes implementing resource management decision-making difficult [4, 6]. In addition, groundwater aquifer boundaries may not align with watershed boundaries. Nevertheless, watersheds provide a natural physiographic area which can serve as a basis for water resources modeling. The modeling results can be very useful in supporting water resources research and in helping to inform planning and management decisions.

Geographic information science (GIScience) theories and geospatial technologies including geographic information systems (GIS), remote sensing, and global positioning systems (GPS) have matured to enable the digital spatial representation of features and processes considered essential in a wide array of social and natural science applications. Moreover, the emergence of geocomputation, or "the art and science of solving complex spatial problems using computers" [7] provides a computational structure for advanced spatial analysis and modeling. Geocomputation has been built upon the initial application of GIS as a geospatial technology developed for the inventory of natural resources [8].

Watershed models, according to Singh and Frevert [9], "… simulate natural processes of the flow of water, sediment, chemicals, nutrients, and microbial organisms within watersheds, as well as quantify the impact of human activities on these processes." Watershed models are often most closely associated with hydrologic models. Under a broader scope water resources models such as stormwater, hydraulic models used for flood modeling, and groundwater models can be applied within watersheds. GIS and other geospatial technologies can play an important role in integrated watershed modeling and management [5, 7].

Hydrologic modeling evolved in parallel with GIS [10]. In particular distributed hydrologic modeling and GIS have shared a parallel and eventually integrated history. The integration of hydrologic modeling and GIS has continued to expand. For example, Korres and Schneider [11] noted that before 1990 the annual number of papers published on GIS and hydrology was less than 10, and in 2015 and 2016 that number increased to 90 per year. A journal of Spatial Hydrology has been established. A number of books have been published on the topic of the integration of GIS and water resources [12–17]. Related books have noted the integration of GIS and water resource modeling and management [4, 6, 9, 18]. Overall, the application of GIS has had a tremendous influence on the field of water resources engineering and science [16] and distributed hydrologic modeling [17]. New advances in a variety of geospatial fields have the potential to significantly enhance the contribution GIS and geospatial theories and technologies can make to watershed modeling.

Encyclopedia of Water: Science, Technology and Society, edited by Patricia A. Maurice.

The intent of this article is to provide an introduction to GIS as applied to watershed characterization and modeling, and in particular for hydrologic modeling. A short history of the development of distributed hydrologic modeling and GIS is reviewed. Definitions for GIS and introductions to the fields of GIScience and geocomputation are provided. GIS as applied to watershed characterization and modeling is discussed covering topics including data models, data acquisition, metadata, georeferencing, fundamental thematic data layers (elevation, land use and land cover – LULC, soils, and social science data), along with issues of scale and data uncertainty. Forms of integration of GIS and watershed models are discussed as well as an example of initial watershed characterization procedures. Resources for exploring the increasing applications for the integration of GIS and watershed models and examples of attempts to categorize applications are presented. Future directions include potential contributions from GIScience and geocomputation, new data, the World Wide Web (WWW), and integrated watershed management.

2 Historical Background

Perhaps the most closely linked connection between GIS and watersheds is through distributed hydrologic modeling. The integration of GIS and hydrology is natural given the large data requirements and inherently spatial nature of distributed hydrologic models [13]. Distributed hydrologic modeling and GIS developed along adjacent paths [19]. In the 1960s and 1970s, their development occurred with few interactions [10], as neither GIS nor water resources models were initially developed to interact with each other [20].

Without a spatial component, hydrologic models have no use for a GIS [13]. However, most water resources and hydrological problems have an obvious spatial dimension [21]. The desire to digitally represent the spatial characteristics of watersheds has a lengthy history. Before the advent of computers, the concept of the grid pattern was proposed to study the spatial effects of hydrologic processes for modeling surface runoff in watersheds [22, 23]. The initial development of digital physically based hydrologic models occurred in the late 1960s [24, 25]. In the decade of the sixties, a new frontier in hydrologic modeling unfolded due to the digital revolution and easy access to the resulting computing capability. For the first time, it became possible to synthesize the entire hydrologic cycle and process large quantities of data. A seminal example of this synthesis was the Stanford watershed model pioneered by Crawford and Linsley [26, 27].

Similarly, the conceptual and automated development of GIS has a long and multi-threaded history dating as far back as the Siege of Yorktown and the use of hinged overlay maps [18]. The first time the term geographic information system was used was in conjunction with the development of the Canadian Geographic Information System in the early 1960s. Led by Dr. Roger Tomlinson, this effort generated a digital natural resources inventory for Canada [8, 28]. Ian McHarg's seminal work, Design with Nature, published in 1969 demonstrated the legitimacy of the overlay technique [28, 29]. The process of overlaying maps to support analysis and decision-making remains a fundamental characteristic distinguishing GIS from other information systems.

In the early 1970s, integrative efforts emerged between GIS and water resources. The authorization of the Florida Water Resources Act of 1972 led to the development of the South Florida Water Management District, which became and continues to be an extensive user of GIS [30]. The Maryland Automated Geographic Information System (MAGI) was developed in 1974 and included the capability to perform water quality studies and produce maps of surface water classifications [30, 31]. The overall approach used by the MAGI system in terms of data acquisition through analysis and planning is not much different than approaches used today, albeit with higher quality data and greater computational capabilities [16].

It was not until the late 1980s that major research efforts began to integrate GIS and hydrologic modeling, driven in part by the desire of hydrologists for more accurate terrain representations [10, 11]. The GIS ARC/INFO developed by Environmental Systems Research Institute (ESRI) was introduced in 1983 and encouraged greater interaction between GIS software and data and water resources scientists and engineers [16]. With the increase in computational capability numerous hydrologic models emerged or were adopted within all levels of government, in private industry and academia in the United States, with similar trends occurring in other countries.

With models becoming more and more distributed, data needs became enormous. GIS provided the technology to manage and process that data. The dramatic increase in computing capability led to enhancements in how hydrologic research was conducted [14]. "The need for a marriage between hydrology and GIS," became apparent [13]. The early 1990s witnessed a tremendous interest in the application of GIS in water resources and hydrology [13]. By the end of the century, hydrologic modeling techniques enabled GIS users to move beyond data inventory and management to sophisticated modeling [10].

By 2000, GIS solidified its contribution to environmental modeling. A GIS could be used to preprocess and validate information and provided an interactive system that could be tightly coupled with an environmental model to easily modify parameters and provide visualizations of modeling results for decision-makers [32]. "What was inconceivable a decade ago is now commonplace in terms of computational power; availability, of high-resolution geospatial data; and management systems supporting detailed mathematical modeling of complex hydrologic processes" [17].

3 Geographic Information Systems

3.1 Definitions

A variety of definitions exist for GIS, and the concepts and fields of GIScience and geocomputation have emerged from GIS. The German philosopher Immanuel Kant defined geographic disciplines as "those disciplines that look at features within their spatial context" [33]. GIS provides a means for integrating digital spatial data acquired at different scales and times, and in different formats. One approach to defining GIS is as an information system. The objective of an information system is to process data into useful information that will help in decision-making. In other words, a chain of steps that leads from observation and collection of data through analysis to use in some decision-making process [34]. Information systems become a function of the data they process. One way to define a GIS is as an information system that handles geographically or spatially referenced data. Broader definitions have also been proposed, e.g. that take into consideration hardware, software, data, networks, people, and procedures for working with spatial data. Others may define GIS as an "automated systems for the capture, storage, retrieval, analysis, and display of spatial data" [35, p. 14], Cowen [36, p. 1554] discussed a variety of approaches for defining a GIS and concluded that, "GIS is best defined as a decision support system involving the integration of spatially referenced data in a problem-solving environment." In terms of watershed characterization and modeling a geospatial database generated and processed in a GIS consists of thematic layers such as elevation, drainage networks, and land cover that share the same georeferencing system and scale (resolution) and their integration (Figure 1).

3.2 Geographic Information Science and Geocomputation

The term geographical information science was introduced by Goodchild [37]. Subsequently, a significant

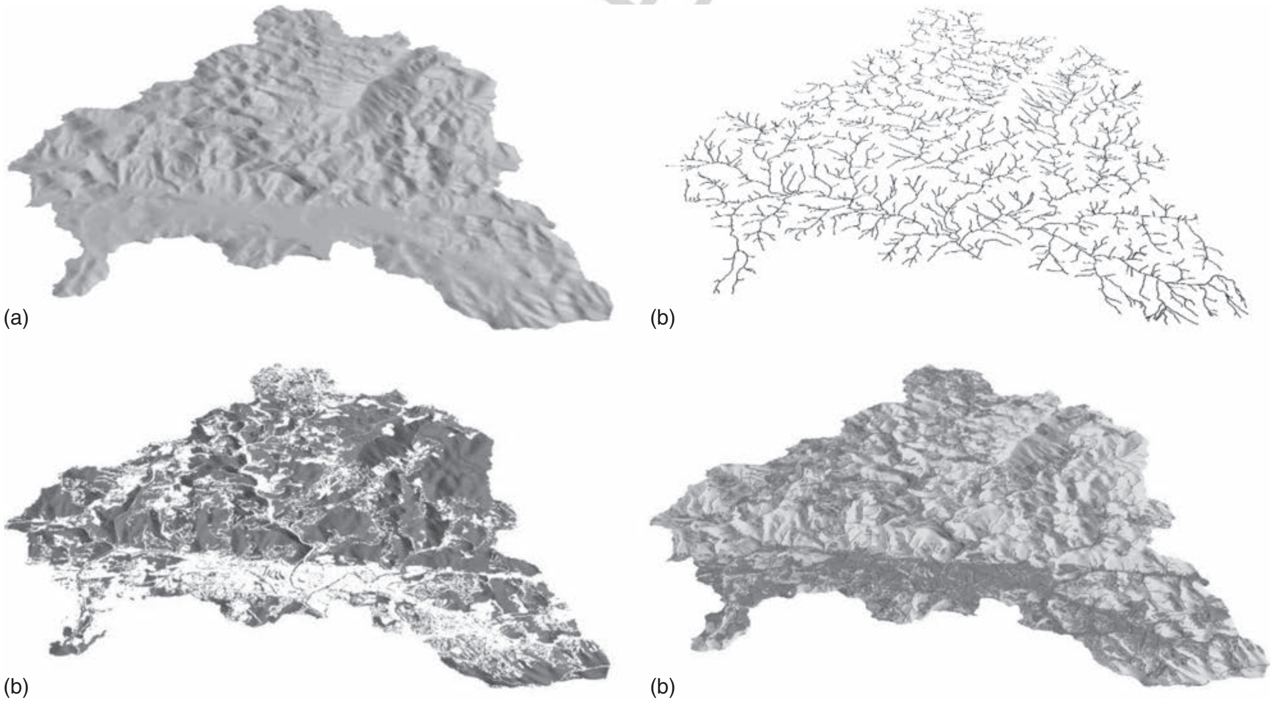


Figure 1 Geospatial database for the Upper South Fork of the New River (USFNR) watershed (80 km^2) located in Watauga County, North Carolina, elevation data represented as a digital elevation model (DEM) at 5 m resolution derived from light detection and ranging (LiDAR) data (a), drainage pattern generated from the DEM (b), forested area classified using 15.24 cm (6 in.) resolution aerial photography (c), composite image consisting of the three layers (areas in grey are primarily impervious surfaces) (d). The layers were processed using the GIS ArcGIS (ESRI, Redlands, CA), and displayed using Blender software (Blender Foundation, Amsterdam, the Netherlands). Source: Blender images courtesy of Dr. Piotr Arlukowicz, University of Gdansk, Poland.

body of literature emerged debating [38, 39] and furthering the development of the concept [40]. Within academia, the term promoted theoretical scientific efforts beyond GIS technological applications [41]. In 1994, the University Consortium of Geographic Information Science (UCGIS) was established, consisting of many of the leading research universities in the field [42]. Journals began changing their names accordingly. For example, the International Journal of Geographical Information Systems (1987–1996) was renamed in 1997 to the International Journal of Geographical Information Science. A substantial literature has since been published on the topic including books [43–48]. A definition of GIScience provided by the UCGIS which has not changed since 2002 [49] states:

> The University Consortium for GIScience is dedicated to the development and use of theories, methods, technology, and data for understanding geographic processes, relationships, and patterns. The transformation of geographic data into useful information is central to GIScience [50].

The first edition of the GIScience and Technology (GIS&T) Body of Knowledge was published in 2006 [51]. The 2.0 version is available in digital form and is designed to be consistently updated (http://gistbok.ucgis.org). Knowledge areas in the 2.0 version include Foundational Concepts, Knowledge Economy, Computing Platforms, Programming and Development, Data Capture, Data Management, Analytics and Modeling, Cartography and Visualization, Domain Applications, and GIS&T and Society. Innovations in these areas will continue to have a strong influence on the development of capabilities and future contributions of GIS to watershed research and management.

Geocomputation emerged from the environment provided by the technological development for spatial data gathering and inventory which was a hallmark of early GIS applications. Openshaw and Abrahart [52 p. 3] stated that “GeoComputation can be regarded, … as the application of a computational science paradigm to study a wide range of problems in geographic and earth systems contexts.” What is unique about geocomputation is its creative and experimental use of GIS, as it emphasizes “process over form, dynamics over statics, and interaction over passive response” [53]. Geocomputation is also considered performing spatial analysis with or without a GIS [53, 54], as researchers often write their own programs, integrate GIS capabilities into their software or with environmental models to perform spatial-temporal analysis. The spirit of innovation, experimentation, and moving beyond the confines of proprietary GIS capabilities permeate geocomputational efforts.

A series of international conferences on GeoComputation initiated at Leeds University, UK in 1996 has been held every other year, alternating with the International Conference on GIScience. The field has generated a significant literature and several books [7, 52, 53, 55–57]. Innovative spatial analysis efforts in watershed modeling that make use of e.g., agent-based modeling (ABM), artificial intelligence (AI), artificial neural networks (ANN), Big Data, distributed and parallel processing, fuzzy modeling, machine learning, geospatial cloud computing, geovisualization, computer programming, volunteered geographic information (VGI), and web-based applications will be informed and enhanced by advances in geocomputation. Increased growth in geocomputational research has also taken place outside academia in the private sector [58]. Geocomputation can have a disciplinary focus as well, e.g. in biology [59]. Dixon and Uddameri [16, p. 5] believe that geocomputation plays a strong role in water resource science and engineering. In this field, they summarize geocomputation as … “GIS-enabled analysis, synthesis, and design of water resources systems,” with a focus on using geoprocessing and computational algorithms to support the development of innovative decision support systems.

3.3 GIS Data

3.3.1 Data Models

Data models define the capabilities and limitations for representing spatial features from the real world in a digital environment. A data model is an abstraction or human conceptualization of reality. According to Tsichritzis and Lochovsky [60], a data model is “a set of guidelines for the representation of the logical organization of the data in a database … (consisting) or having named logical units of data and the relationships between them.” Peuquet [61] defined data models “as a general description of specific sets of entities and the relationship between these entities.” A data model is an abstraction or human conceptualization of reality. Often the term data model and data structure are used interchangeably when working with spatial data. For this article, we will follow the convention described by Peuquet [61], and that a data structure determines the detailed arrangement of data based on a data model. By this definition, a data structure determines how a data model is represented in a particular GIS.

Basic types of data models include vector and tessellations. The standard vector data model consists of points, lines, and polygons with an associated attribute table. The topological or spatial relationship information between those elements is explicitly encoded in the data file. A vector data model represents discrete features like a point for the outlet for a watershed, a line for a stream or river, and a polygon for a sub-basin of a watershed or the boundaries of the watershed itself. Tessellation models represent a repeating pattern. Regular tessellations can be in the form of a triangle, hexagon or as a square commonly referred to a raster. The spatial relationship information of features on a raster layer are implicitly encoded within a 2-D array of rows and columns. A raster data model can represent continuous surfaces, wherein the values can change every grid cell (e.g. elevation). A digital elevation model (DEM) is a raster layer introduced by the U.S. Geological Survey which represents elevation in an array of regularly spaced grid cells. Vector and tessellation data models are logical duals of each other as vector data represents discrete objects and tessellation models represent a unit of space [61]. Water resources models extensively use both vector and raster data.

Other notable data models useful for watershed modeling and management include triangular irregular networks (TIN), object-oriented data models, and voxels. TINs consist of Delaunay triangles created by lines drawn between points that do not overlap [62]. Elevation data are commonly represented as a TIN. The advantage of a TIN is that the surface is constructed by connecting actual sample points rather than estimating values between sample points interpolated mathematically and statistically as when constructing a DEM from sample points. A disadvantage of a TIN is that it is not as readily combined with other raster or vector thematic watershed data layers for analysis. TINs are often used for flood modeling and DEMs are often used for drainage pattern analysis.

An object data model can be useful for representing discrete features such as a river reach [63] or watershed and the relationship between features. Rather than storing geometric information describing features separately from their corresponding attribute data as with a vector data model, information regarding the geometry, topology, attributes, and behaviors (e.g. changes in state of hydrologic behavior) are encapsulated and stored as part of the object. Object data models follow the philosophy of object-oriented programming and its three main tenants of encapsulation, inheritance, and polymorphism. Since the early 1990s, object data models have contributed to studies in water resource management [64–66] and hydrologic modeling [63, 67, 68].

The models discussed thus far are primarily represented in 2-D as a planar surface with x, and y coordinates, or in $2\frac{1}{2}$ D such as a DEM or TIN with a z value representing elevation. In a true 3-D representation, a data model also represents volume. Voxels are a 3-D representation of a raster grid cell with length, width, height, and volume. Voxels can be envisioned as stacked blocks that can represent 3-D features in the atmosphere, on the landscape, or underground. Voxels provide a data model with which to characterize and potentially integrate into watershed models a 3-D representation of the atmosphere [69], tree canopies [70], streams and riparian areas [71], stream bank erosion [72], geologic structure [73], and the temporal dimension of geospatial processes [74].

3.3.2 Data Acquisition

Acquiring GIS data is one of the most time-consuming aspects of developing a GIS database for watershed characterization and modeling. Essentially, there are two main approaches data capture and data transfer [75]. Data capture can be subdivided into primary data capture wherein data are collected through direct measurement and secondary data capture in which data are converted from other sources. Data transfer refers to acquiring already assembled datasets, for example through spatial data geoportals on the WWW. An advantage of the data capture approach is that the user directly controls data quality and character. A disadvantage is the expense in design, implementation, and management of data gathering projects. An advantage of the data transfer approach is the conservation of time and resources. Disadvantages include that the data may not be relevant, current, or provided at a useful scale, and the quality of the data may not be known. With the wealth of spatial data available today, data transfer is the more economical approach to begin a data acquisition project.

To find already existing spatial data and to begin evaluating the relevance and quality of the data for a specific project requires metadata [75]. Metadata are information describing spatial data [62]. Metadata are required for spatial data to be useful and include characteristics such as the data model, georeferencing system, cartographic scale or resolution, when the data was acquired, spatial accuracy, lineage, and source. In the United States, the Federal Geographic Data Committee (FGDC) was tasked by Executive Order in 1994 to enable access to the National Spatial Data Infrastructure (NSDI), and to support the creation, management, and maintenance of metadata. The FGDC has supported the Content Standard for Digital Geospatial Data Metadata (CSDGM) metadata standard; however, it is in the process of adopting the International Standards Organization (ISO) geographic metadata [76].

3.3.3 Georeferencing

The absolute location of features in a GIS data layer can be represented using spherical coordinates (latitude and longitude) or by using planar coordinates. Although analysis can be done with data represented using spherical coordinates, it is easier to do calculations in a planar Cartesian coordinate system for which many algorithms exist. A planar georeferencing system consists of three elements a projection, a datum, and a coordinate system. The projection refers to the process of transforming the spherical coordinates to planar coordinates representing a flat surface. The projection process always incurs some amount of distortion. The two characteristics most often desired to be retained for GIS data layers are either conformal or equal-area properties. Conformal projections retain the shapes of features on the earth's surface, whereas equal area projections retain the same area for features. These can be important considerations especially for study areas of large spatial extent. The datum provides a frame of reference for locations on the earth's surface. A local datum, such a North American Datum 1927 (NAD27), has a point of origin and fits a limited area on the earth's surface very well. Earth-centered global datums such as the North American Datum 1983 (NAD83) and the World Geodetic System 1984 (WGS84) fit the entire earth well overall. The difference in location provided by a local datum (e.g. NAD27) and that provided by an Earth-centered datum (e.g. NAD83) can be hundreds of meters. If two GIS data layers do not seem to overlay properly, it may be because they have the same projection and coordinate system, but different datums. A planar coordinate system provides a grid for cartesian x and y coordinates. Two examples of coordinate systems are the Universal Transverse Mercator (UTM) coordinate system originally designed for military purposes and which is used globally, and the State Plane Coordinate System (SPCS) used in the United States [62, 75].

Georeferencing terms are sometimes used interchangeably, which can be a source of confusion. For example, the SPCS may be listed as an option under projections in a GIS. However, the SPCS is based on different projections for different states. East-west trending states are based on the Lambert Conformal Conic projection and north-south trending states are based on the Transverse Mercator projection. When initiating the development of a watershed GIS database it is important to select and use the same georeferencing system (projection, datum, and coordinate system) for all layers.

3.3.4 Fundamental Thematic Data

3.3.4.1 Elevation

Elevation or terrain data are a key dataset to use for watershed characterization and modeling. Topographic data can be represented using different data models such as vector contour lines, a raster DEM or as a TIN [62]. Perhaps the most commonly used elevation data model for watershed modeling and management is a DEM. Traditional sources of elevation data include surveying and the USGS's use of line trace contour-to-grid interpolation from digital line graphs [77]. Newer data sources include light detection and ranging (LiDAR) and synthetic aperture radar (SAR). In the United States, DEM data generated using traditional methods and LiDAR are available at 3, 10, and 30 resolutions through the USGS National Elevation Dataset (NED). An example of DEM data available globally is from the Space Shuttle Radar Topography Mission (SRTM) using SAR and interferometry to produce 30 m resolution DEMs for 80% of the Earth's surface.

LiDAR technology uses laser pulses of light that record the position of detected features to create a vector point cloud that is processed to remove above ground features in order to produce bare earth or elevation data. LiDAR data can be acquired using aerial lidar systems (ALS) (Figure 2), mobile lidar systems (MLS), or terrestrial lidar systems (TLS). DEMs have been created combining LiDAR data from all three sources, for example, for flood modeling [78] (Figure 3). The resolution of DEMs derived from LiDAR data continues to improve and is becoming more widely available. For some locations in the United States, 1 m resolution LiDAR DEMs are available through the USGS National Map 3DEP Program, and Geiger LiDAR data provide DEMs created using 8 pts per m^2 for some parts of North Carolina through the North Carolina Emergency Management.

3.3.4.2 Land Use/Land Cover

LULC layers are important datasets for watershed characterization and modeling due to their influence on hydrologic processes and their utility, for example, for estimating hydraulic roughness coefficients [17] and the U.S. Soil Conservation Survey's Curve Numbers (CN) [16]. Strictly speaking, land cover refers to features that cover the earth's surface like coniferous or deciduous trees. Land use is an economic term and represents how the land surface is being used or modified by humans. Classification systems sometimes combine both representations [79]. LULC datasets are often derived using remotely sensed imagery. Using a standard classification system is important to ensure transferability of results. A general classification system such as Anderson et al. [79] or a regional classification system can also be refined for local watershed applications [80]. A common dataset used in the United States is the 30 m resolution National Land Cover Dataset (NLCD) [81]. The categories were classified using Landsat 5 Thematic Mapper (TM) multi-spectral satellite imagery. A useful geoportal for accessing LULC data for the United State and globally is the USGS Get Land Cover Data website. Medium resolution satellite imagery acquired by the Landsat series of sensors can provide a long-term record

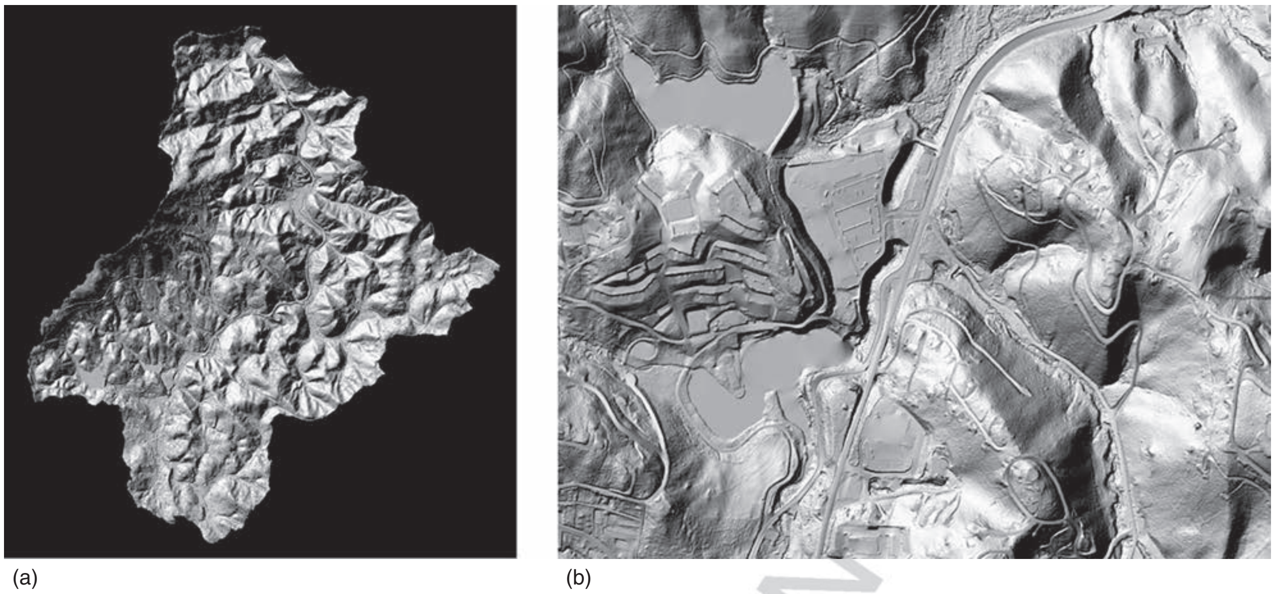
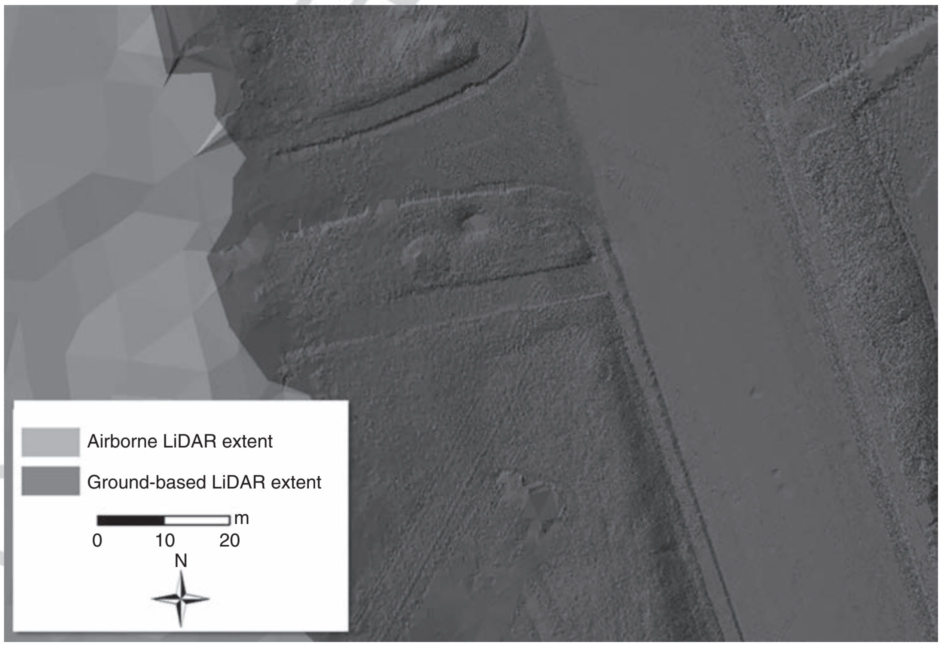

(a)
(b)

Figure 2 DEM generated from aerial (helicopter) LiDAR data (horizontal resolution = .5 m^2) depicting (a) the Middle Fork sub-basin in the USFNR watershed in Watauga County, North Carolina (a), and a subset of the DEM for the Middle Fork sub-basin (b). Source: LiDAR data courtesy Tuck Mapping Solutions, Inc., Big Stone Gap, VA.

Figure 3 A composite triangulated irregular network (TIN) consisting of merged bare-earth airborne, mobile, and terrestrial LiDAR data, located in the Boone Creek sub-basin of the USFNR watershed in Watauga County, North Carolina. The ground-based LiDAR data (mobile, and terrestrial) cover the right two-thirds the image (3 cm vertical RMSE). Source: Mobile and terrestrial data courtesy of ESP Associates, Inc., Fort Mill, SC [78].



for studying LULC change in watersheds. Fine resolution land cover data can be classified using IKONOS, GeoEye, Quickbird, and WorldView imagery, and georeferenced aerial photography such as digital orthophoto quarter quadrangles (DOQQs). The U.S. Department of Agriculture provides National Agriculture Imagery Program (NAIP) leaf-on imagery in DOQQ format at 1 m resolution. Since aerial photography does not have the spectral resolution of multi-spectral satellite imagery different software and image processing methods are required for classification. For example, Feature Analyst (Geospatial Solutions, Sterling, VA) uses geocomputational approaches such as machine learning and pattern recognition to classify high resolution ($\leq$1 m) aerial photography (Figures 4 and 5).

With rapidly developing remote sensing technologies such as LiDAR and structure-from-motion (SFM) 3-D vector point clouds can be acquired and used to

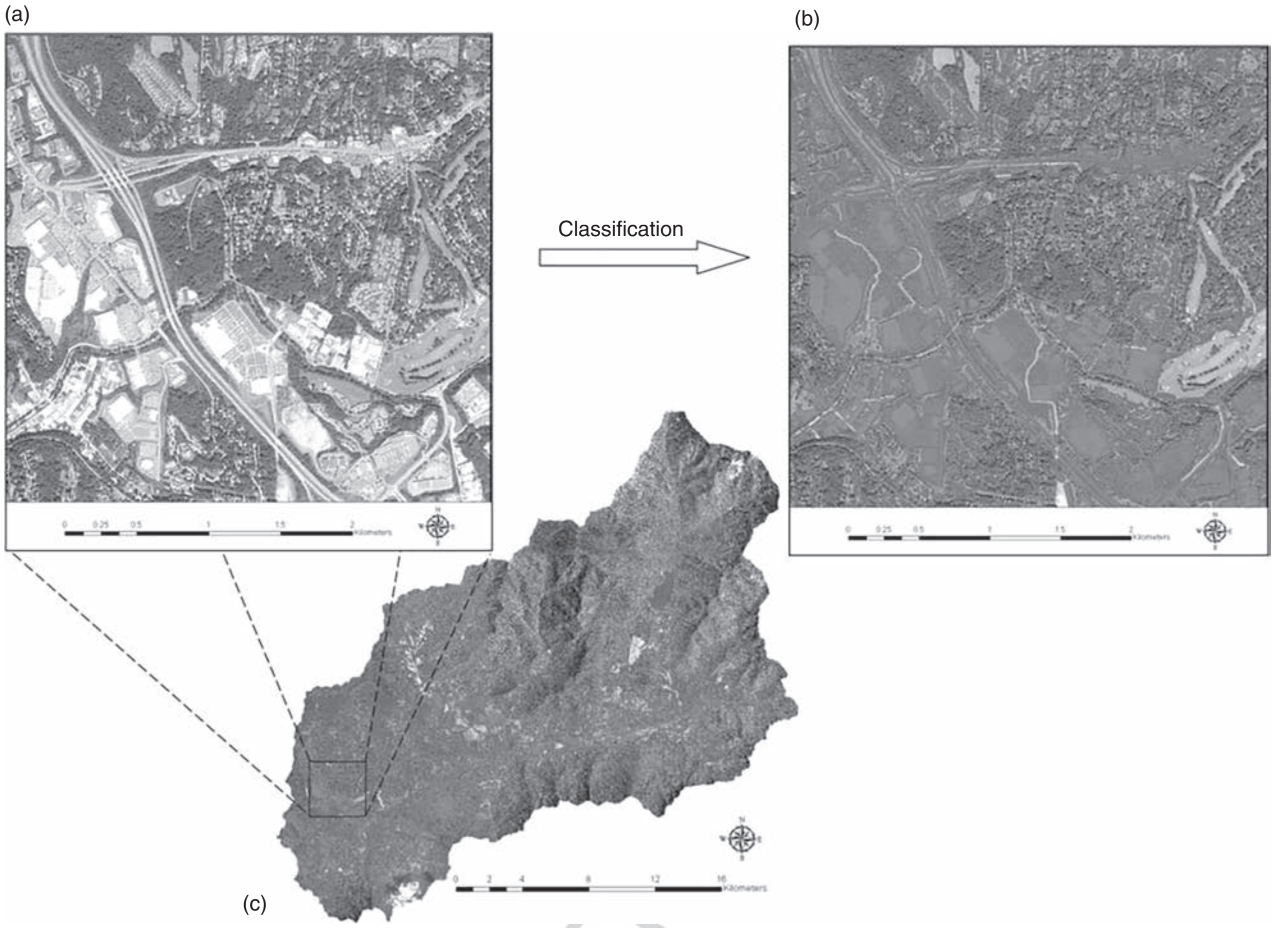


Figure 4 Impervious surface classification from aerial photography, 2005 NAIP imagery (1 m resolution) of a section of the Swannanoa watershed, Buncombe County, North Carolina (a), impervious surface classification for a section of the Swannanoa watershed (b), impervious surface classification of the Swannanoa watershed (c) [82].

characterize watershed features. LiDAR data whether acquired using ALS, MLS, or TLS platforms can be used to generate 3-D point clouds. Application examples within watersheds include using ALS data to characterize forest structure and using TLS data for geomorphological studies [84]. Point clouds can also be generated using unmanned aerial systems (UAS), commonly referred to as drones. With a digital camera attached to the UAS, overlapping photographs are taken along flight lines across a study site and SfM photogrammetric techniques are used to identify common points within the photographs from which to create a 3-D point cloud [85] (Figure 6). These 3-D point clouds can be used for a variety of watershed characterization applications such as land cover classification [86, 87], evaluation of gully systems [88], characterization of fluvial topography [89], and the generation of digital surface models (DSM) to predict shade cast by vegetation in riparian areas [86]. Also, algorithms exist for constructing voxels from the point cloud data, and the potential for applications in physical geography are evident although not yet fully realized [90].

3.3.4.3 Soils

Another important thematic layer for hydrologic studies is soils data. Soils maps are key for modeling infiltration processes, groundwater recharge, and saturation excess runoff. The United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) has been conducting soil mapping since 1899. The two most widely used soils databases are the Soil Survey Geographic Database (SSURGO) and the State Soils Geographic Database (STATSGO). The SSURGO data were collected at scales ranging from 1:12,000 to 1:63,360. The component soils and their properties for each unit are linked to the maps in the database. The STATSGO database is a broader-based inventory and generalization of the SSURGO database. The STATSGO database has been superseded by the Digital General Soil

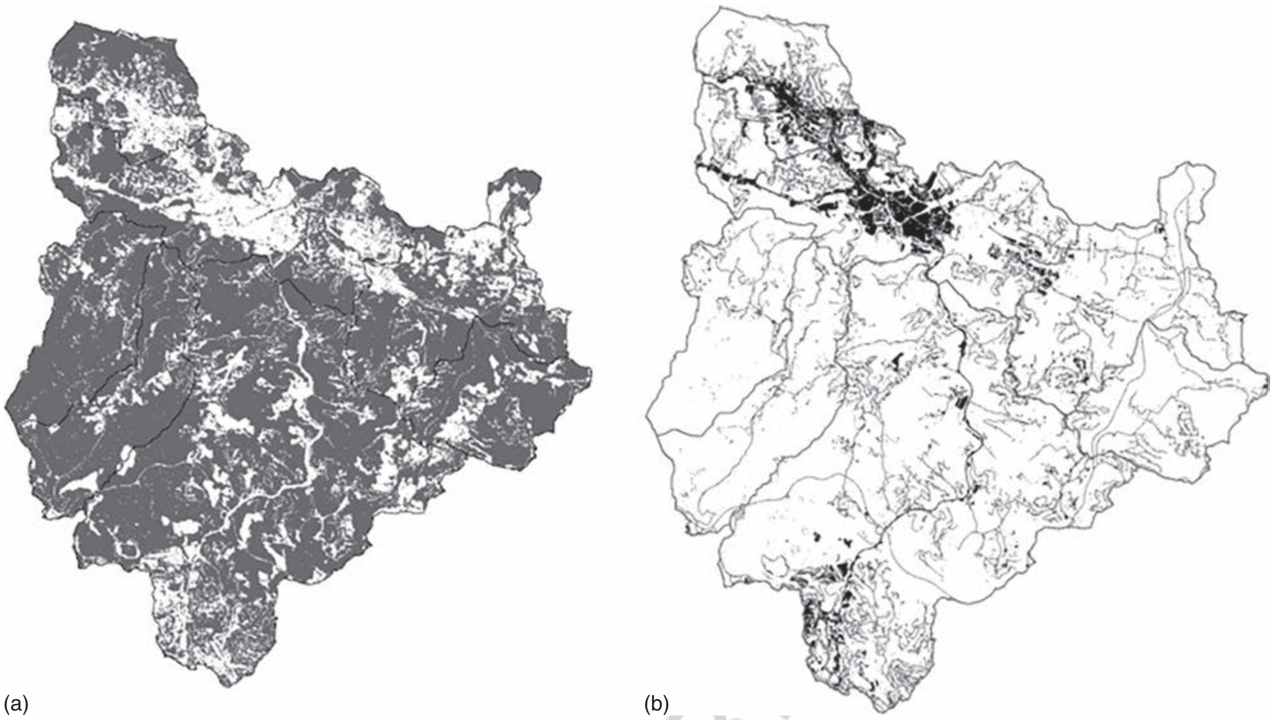


Figure 5 Forested and impervious surface classification from aerial photography for the USFNR watershed in Watauga County North Carolina, classified using 2010 leaf-off 15.24 cm (6-in.) resolution aerial photography, forested (a), impervious surfaces (b). The Town of Boone is located in the upper portion of the watershed [83].

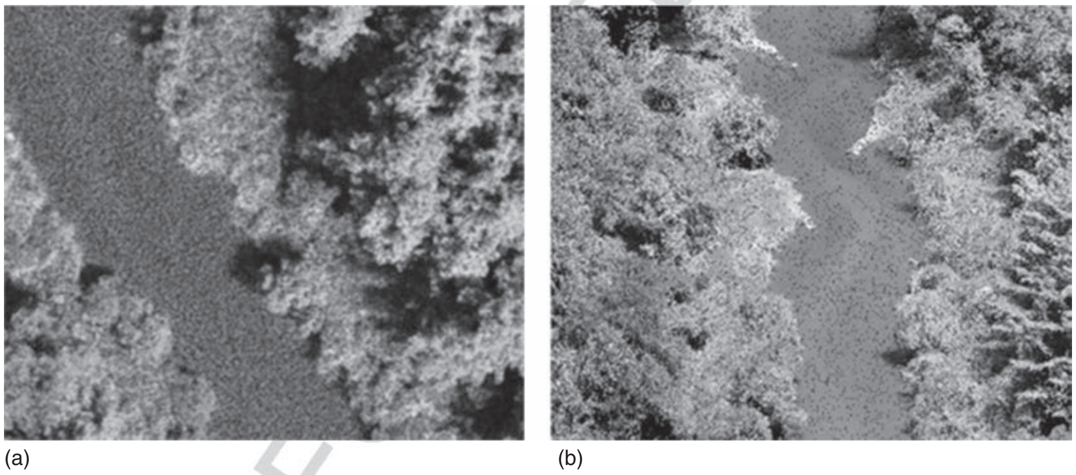


Figure 6 Riparian area of the New River in the USFNR watershed in Watauga County, North Carolina. Nadir (a) and oblique (b) view of a dense 3-D point cloud (forests 1717 pts m^{-2}, river 644 pts m^{-2}), generated using digital photographs taken from an unmanned aerial system (UAS) and processed using structure-from-motion (SfM) software [86].

Map of the United States (STATSGO2). The Web Soil Survey website provides access to these datasets.

3.3.4.4 Social Science Data

As efforts are made to move forward with more integrated watershed modeling, questions arise as to how to better integrate social science data and the human dimension in computational watershed models. The need for this integration has been recognized and is increasingly being focused upon [91–93]. Moving from the inclusion of demographic data (e.g. U.S Census), physical characteristics (e.g. land use), and economic characteristics (e.g. tax parcel cost) and attempting to incorporate values, beliefs and perceptions is challenging

[94]. Geocomputational approaches such as ABM, cellular automata, and spatial decision support systems (SDSS) may provide useful approaches to pursue [93, 94]. This integration can be thought of not only as the representation of the human dimension in models, but also through contributions to watershed characterization and model development, for example through crowdsourcing with a spatial dimension [95], and citizen science [96]. In addition, stakeholder input can drive water resources applications [16].

3.3.5 Issues of Scale

The term scale has several definitions when referring to GIS data layers. Cartographic (map) scale refers to the proportion of the distance on a map to the corresponding distance on the ground. For example, for a 1/10 000 scale map, 1 in. on the map equals 10 000 in. on the ground. A 1/10 000 scale map covers a smaller spatial extent and provides more detail. A 1/5 000 000 scale map covers a larger spatial extent and provides less detail. Geographic (extent) scale refers to the observational scale or size of the study area, wherein a larger scale refers to a larger area and a smaller scale refers to a smaller area. Cartographic and geographic scales are commonly used interchangeably but represent different concepts. For example, a small cartographic scale map represents a large area, and a small geographic scale map represents a small area. Measurement (resolution) scale refers to a grid cell or pixel size. A coarse resolution refers to a large cell size and a fine resolution refers to a smaller cell size. Operational scale refers to the scale at which processes operate [97].

Converting between GIS data layers represented using different data models, such as vector to raster requires familiarity with definitions of scale. To convert a vector layer with features represented by lines and polygons the following rule can be used: "divide the denominator of the cartographic map scale by 1000 to get the detectable size in meters. The resolution is half of the amount" [98]. For example, for a 1/10 000 scale map, the detectable size is 10 m and the resolution is 5 m. For determining the appropriate grid cell size for a DEM to be generated using LiDAR bare earth point data, a point area relationship can be calculated using the following equation [98–100]:

$$d = \sqrt{A}/n$$

where d, average horizontal resolution; A, area; and n, the number of points. This relationship can be calculated in GIS software such as ArcMap desktop.

The scale or resolution at which geographic thematic data is represented for watershed characterization and modeling is an important consideration. Issues of scale have been a central area of inquiry in the GIScience field [97, 101–103]. The primary goal is to ensure that features are represented as accurately as possible. A common initial approach is to use finest scale or resolution data that is available. However, this may not be necessary if features can be sufficiently represented at coarser resolutions. Potential drawbacks for using the finest resolution data include increased data storage requirements, computational power, and processing time. Finding the optimal scale or resolution at which to represent landscape features in a watershed, particularly regarding elevation data, has received a significant amount of attention [17, 104–107], including a recent focus on LiDAR data [108–110].

Issues of scale regarding land cover data are also important. For example, the total impervious area (TIA) within a watershed can have a strong impact on stormwater management, water quality, and stream health. Look up tables have been available for obtaining an approximate measure of stream health based on TIA [111, 112]. When making a link between TIA and stream health important factors to consider are the source and method used for generating the impervious surface data layer. For example, the TIA calculated within a watershed could be significantly different if the impervious layer was generated by classifying a multispectral 30 m Landsat satellite image than if the layer was generated by classifying 1m aerial photography. Dixon and Uddameri [16, p. 10] provide a table that includes sources of impervious surface information.

Evaluating the influence of the scale and resolution of thematic GIS data can be undertaken using a range of quantitative metrics including fractals, Fourier and wavelet analysis, and geostatistics [103]. A fundamental principle upon which fractals are based is the concept of self-similarity, which describes the repeating patterns of features at different scales [113]. When thematic GIS data is smoothed or aggregated the information loss that occurs with respect to cell size can be described by fractal scaling laws [17, 103], and can be measured, for example using the fractal dimension D [16, 114]. Examples of the application of fractals within watersheds include properties of stream networks [115], and the influence of DEM resolution [116], soil properties [117], and modeling response units (MRU) [118]. With greater availability of finer scale data, for example, from LIDAR and SfM sources issues of scale and representation are going to remain important considerations for watershed characterization and modeling.

3.3.6 Data Uncertainty

The uncertainty associated with spatial data is another key area of concern and research in GIScience as error-laden data can lead to inappropriate decisions [119]. The process of entering and storing the representation of complex real-world features in a digital environment is error-prone, and uncertainty exists at every level. Uncertainty describes the difference between how a feature actually exists in the real world and how it is represented in a computer environment [120]. Uncertainty can be generated from different sources, including the precision or accuracy of an instrument, measurement error, or the difficulty in defining the phenomena being measured. Uncertainty can describe the degree of accuracy of a measurement [121]. In general, uncertainty has been used as a catchall term that describes the incomplete digital representation of phenomena and a general measure of representation quality [75]. The U.S. FGDC provides five standards of quality: positional accuracy, attribute accuracy, logical consistency, completeness, and lineage [122].

As geospatial technologies for acquiring spatial data continue to evolve new standards are required for determining data quality. The USGS and the National Digital Elevation Program (NDEP) sponsored the U.S. National Enhanced Elevation Assessment (NEAA), an effort starting in 2010 to quantify the value of a national LiDAR program [123]. In response to this study, the USGS National Geospatial Program (NGP) established the 3D Elevation Program (3DEP) program in 2013, and base specifications were established for LiDAR data. These base specifications initially included five quality levels. In version 1.1 of the LiDAR Base Specification (LBS) efforts were made to align the quality levels to those proposed by the American Society of Photogrammetry and Remote Sensing (ASPRS), and an additional quality level 0 was added as a placeholder for anticipated higher quality data. Quality level 2 was established as the minimum quality level for LiDAR data collection by the USGS-NGP [124]. Current 3DEP quality level specifications are provided in Table 1.

The uncertainty inherent in spatial data can affect the quality of watershed characterization and modeling results in several ways. Source data errors are transferred directly into the geospatial watershed database. Uncertainty in source data can then propagate through the geospatial database and is compounded through processing and analysis procedures [126]. Ideally, information regarding data uncertainty was recorded and is available in accompanying metadata including data acquisition information, lineage procedures, accuracy of instruments, and quality control measures. Fundamental questions to be asked include (but are not limited to) are the data temporally relevant, were accuracy assessments performed (e.g. for classified land cover layers), and are landscape features being sufficiently represented? For example, is the grid cell size for representing elevation data appropriate given the point/area relationship, and does the selected grid cell size represent the terrain features well? Methods are available for evaluating the representation of terrain features [127], and in contrast to other interpolation routines, Kriging provides an estimate of appropriate grid cell size through evaluating the distribution of residuals [128].

4 Integration of GIS and Watershed Models

GIS and water resources modeling technologies were not originally designed to interact with each other; however, the visual display, spatial analysis, and data management capabilities make GIS an attractive technology to link with predictive modeling [20]. Linkages or an interface between GIS and geospatial databases and hydrologic programs, as well as other watershed models, can be created to support watershed characterization and modeling. For example, the integration of a GIS and hydraulic models can be undertaken to perform flood modeling within a watershed. In terms of spatial representation fundamental forms of hydrologic models include lumped, semi-distributed and distributed models [129]. Lumped models treat a watershed and thematic layers as homogenous units from which an outflow hydrograph is calculated from rainfall excess [23, 130]. Although it lacks spatial definition of watershed characteristics, one advantage of lumped models is computational efficiency.

Semi-distributed models spatially discretize watersheds based on sub-basins or hydrologic response

Table 1 Data quality levels and related accuracies.

QL	Source	Pulse density (m^{-2})	DEM cell size (m)	Vertical RMSE (cm)
QL 1	LiDAR	8 pts	0.5	10
QL 2	LiDAR	2 pts	1	10
QL 3	LiDAR	0.5 pts	2	20
QL 4	Imagery	n/a	5	139
QL 5	IFSAR	n/a	5	185

Source: Adapted from [125].

units (HRU) also referred to as grouped response units (GRU) or MRU [118]. HRUs are represented as irregular finite elements [23], based on characteristics such as aspect, slope, soil type, vegetation, and precipitation distribution, and the hydrologic response is calculated for each unit [131]. Semi-distributed models provide a compromise between lumped models and fully distributed models in terms of data and computational requirements. Hydrologic models which utilize HRU's include the Soil and Water Assessment Tool (SWAT) [132] and the Precipitation-Runoff Modeling System (PRMS) [133]. GIS and thematic geospatial databases are used extensively for delineating HRUs [136].

In comparison to lumped and semi-distributed models, fully distributed models are based on a grid cell or even TIN [137] representation of parameters and are spatially complex often with unknown parameters. Beven [138] describes some of the challenges with distributed modeling including nonlinearity, scale, equifinality, uniqueness, and uncertainty. However, with increases in data availability and computational capability distributed physics-based watershed modeling is feasible across a range of applications [139]. Commonly used fully distributed hydrologic models include MIKE SHE [139, 140], and ANSWERS [141]. Eco-hydrologic watershed models have also been designed with remote sensing and GIS routines that calculate water, carbon, and nutrient mass balances on a grid cell basis [142]. For a more comprehensive list of hydrologic models see Singh and Woolhiser [143]. Linkages of GIS and watershed databases with semi-distributed and distributed models have increased significantly since the beginning of the twenty-first century [11, 14, 16, 17].

The integration of GIS and hydrologic and other watershed models can take different forms primarily through loose coupling, tight coupling, and system enhancement [11, 20, 144]. Loose coupling is the most common form of integration, wherein water resources geospatial data is generated within a GIS and then transferred in the form of a data file to a hydrologic model for spatiotemporal modeling. Tight coupling occurs when hydrologic or hydraulic model capabilities are enacted within a GIS and geospatial data is generated for use in the model (or vice versa). An example of a tightly coupled integration would be the activation of the extension Arc Hydro Tools [145] in ArcGIS. Other example hydrologic/hydraulic extensions utilized in ArcGIS include HEC-GeoHMS and HEC-GeoRAS used for generating export data files which are imported (loose coupling) into Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) [146] and Hydrologic Engineering Center–River Analysis System (HEC-RAS) [147]. System enhancement is when modeling capabilities are written into the code of the GIS software and are automatically available for use upon program startup. An example of system enhancement is the inclusion of the Hydrology (Toolset) in ArcGIS. Martin et al. [20] provides an extended listing of GIS and water resources model interfaces.

The integration of GIS and watershed models can enhance procedures for geospatial watershed database development. An important initial procedure for watershed characterization is drainage pattern and watershed boundary delineation using a DEM. One of the early influential papers describing the steps in this process was written by Jenson and Domingue [148]. The essential steps include filling sinks or depressions in the DEM, calculating flow direction based on an eight-direction pour point algorithm, calculating flow accumulation, selecting a flow accumulation threshold that will realistically represent the drainage pattern, selecting an outlet for the watershed, and delineating the watershed boundary through identifying all the elevation cells that drain to that outlet. An initial conditioning step can also be used to "burn in," the drainage pattern using an already available drainage pattern layer, for example from the U.S. Geological Survey's National Hydrography Dataset (NHD) or a regionally developed streamline dataset. A key step in this process, even if a drainage pattern layer is already available, is to carefully consider the selection of the flow accumulation threshold. Using a flow accumulation threshold that is too low will result in a drainage pattern that is too dense, extending beyond the limits of perennial streams. A flow accumulation threshold that is too high will result in a sparse drainage pattern, with a corresponding underestimation of the drainage density for the watershed. Verification and quantitative evaluation of the accuracy of the derived drainage pattern should be conducted, for example using georeferenced aerial photography [83]. Once the outlet is selected and the watershed boundary delineated a watershed mask can be created and used in an overlay process to clip geospatial thematic layers to the boundaries of the watershed. This process is represented graphically in Figures 7–10 using a DEM generated from Satellite Pour l'Observation de la Terre (SPOT) satellite imagery and the ArcHydro Tools extension in ArcGIS. The location is the Raikot Basin on the northern slopes of the Nanga Parbat Massif in the Karakoram Mountain Range in northern Pakistan. Flatter terrain presents challenges to effectively executing this process, and research is ongoing in terms of how to delineate drainage patterns in areas with a lack of topographic relief [149]. After drainage pattern and watershed boundary delineation, morphometric analyses such as stream order, stream length, bifurcation ratio, drainage density, and elongation ratio can be calculated [150].

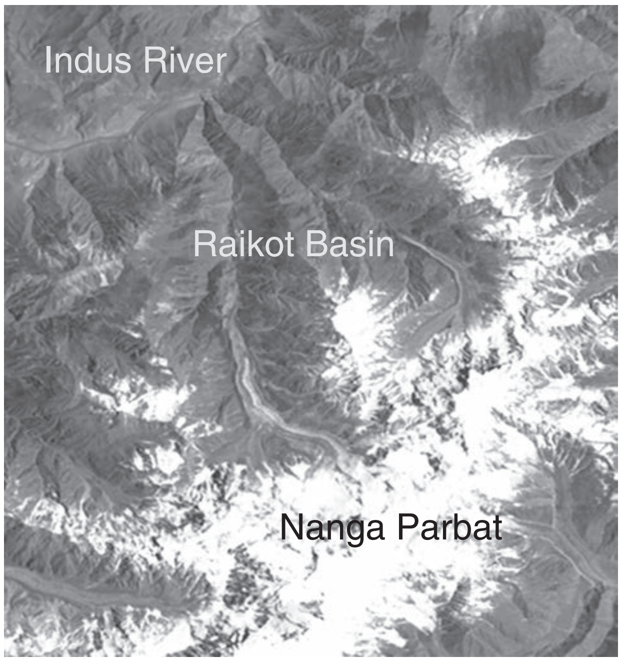


Figure 7 SPOT multispectral satellite image (20 m resolution) of the northern slope of the Nanga Parbat Massif (8126 m), including the Raikot Basin and the Indus River (1000 m), in the Karakoram Mountain Range in northern Pakistan. Extreme relief is exhibited along the 21-km distance from Nanga Parbat to the Indus River. Source: Spot imagery courtesy of Dr. Michael Bishop, Texas A&M University.

Some issues that arise from the interfacing of GIS and watershed models include the lack of established conventions, protocols, and guidelines [20, 151]. GIS programs, extensions, and models are continually updated and at times may not be compatible with each other. Tight and loose coupling is technology based and does not address conceptual differences between GIS and hydrologic models, specifically the conceptualization of time and space are often not compatible between GIS and hydrologic models [10]. Issues with massive amounts of data [151], currently referred to as Big Data may continue to pose challenges. In the future, hybrid systems may emerge using geocomputational approaches, open source software and Web-based GIS programs [152].

4.1 Areas of Applications of GIS to Watersheds

The opportunities to apply GIS and geospatial theory and technology to watershed characterization and modeling are extensive. Published books have covered a range of applications over the years [12, 14–16, 153]. During a period of 25 years starting in 1993, the American Water Resources Association offered 10 specialty conferences on GIS and Water Resources, and the proceedings from the conferences are a valuable source of knowledge and information regarding applications. Sui and Maggio [10] provided an extended list of GIS and hydrological modeling applications. The publication of application-based journal articles continues to expand in terms of numbers and breadth of topics [11].

Authors have also proposed application categories, for example Korres and Schneider [11] listed applications according discipline (surface hydrology, groundwater hydrology, water resources management, waste and stormwater management, floodplain management, water quality analyses, water resources monitoring, and forecasting and engineering…), principal use (hydrological inventory, monitoring of hydrological status, design and planning of infrastructure, forecasting hydrological processes, and early warning systems), and principal user (engineers, scientists, and the public) in the areas of administration, private enterprise, industry, science, and public use in particular web-based applications. Dixon and Uddameri [16] described applications in thematic areas: watershed impact assessment, aquifer vulnerability characterization using multi-criteria decision-making models, coupling of GIS with physics-based mass balance approaches, coupling of GIS with statistical methodologies, and GIS use in water and wastewater applications. Additional application areas include but are not limited to: irrigation and drainage [154], restoration [155], riparian studies [156, 157], geovisualization [158], impacts of climate change [159], and integrated watershed management [93].

5 Future

The field of GIScience provides a rich framework within which to pursue key advancements in geospatial conceptual and technological areas relevant to improving the integration of GIS and watershed models. Current topic areas are outlined in the 2.0 version of the GIScience and Technology Body of Knowledge (http://gistbok.ucgis.org). For example, a better theoretical understanding of space and time will enhance the interface between GIS and watershed models (Foundational Concepts). Advancements in Computing Platforms could come from research in computing infrastructure (the cloud, use of mobile devices, cyberinfrastructure), high-performance computing, and social media analytics (e.g. for detecting emerging events such as floods within a watershed), and software systems (AI, and Web-GIS). Improvements in data acquisition using UAS's and VGI (Data Capture) would be beneficial. Under the topic of Data Management, innovations could be made regarding data models for representing real-world features in a digital environment and multi-dimensional representations. Additional contributions could be provided in Analytics and

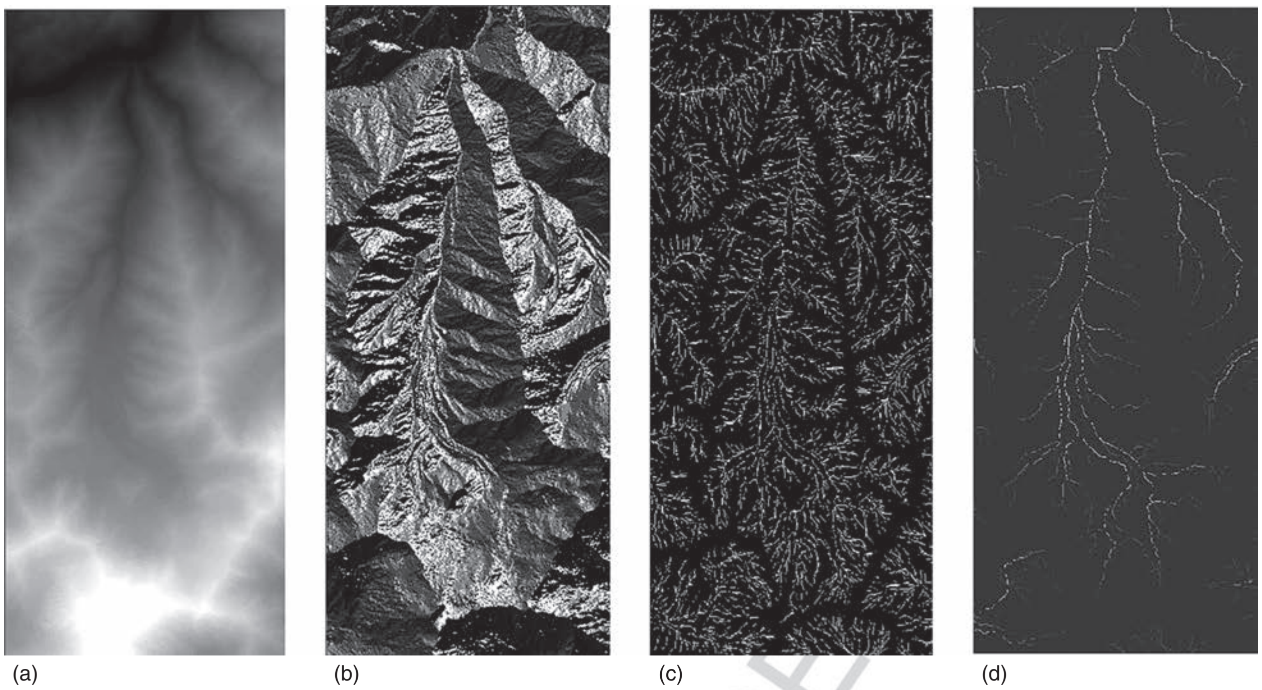


Figure 8 DEM (20 m) generated from SPOT satellite panchromatic stereo pairs of the Raikot Basin area (a), flow direction (b), flow accumulation (c), drainage pattern after the flow accumulation threshold was selected (d). Source: DEM courtesy of Dr. Michael Bishop, Texas A&M University.

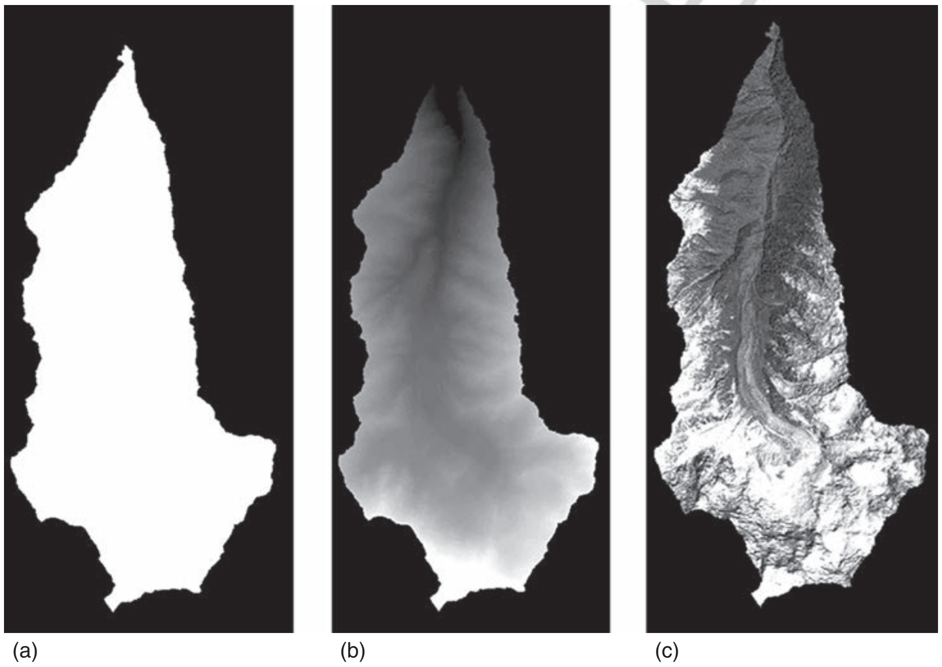


Figure 9 Raikot Basin mask (a), DEM of the Raikot Basin (b), SPOT multispectral imagery draped over the DEM of the Raikot Basin (c).

Modeling including spatial statistics, cellular automata, ABM, and space-time analytic modeling. Innovations in Cartography and Visualization could be made in the areas of mapping uncertainty, terrain representation, web mapping, big data visualization, geovisualization, and geovisual analytics. Related Domain Applications include Earth science research, emergency response, environmental science and management, hydrologic and hydraulics, and water resources. In the area of Geographic Information Science and Technology (GIST) & Society, further research in public participation GIS, spatial decision support, and the contribution of citizen

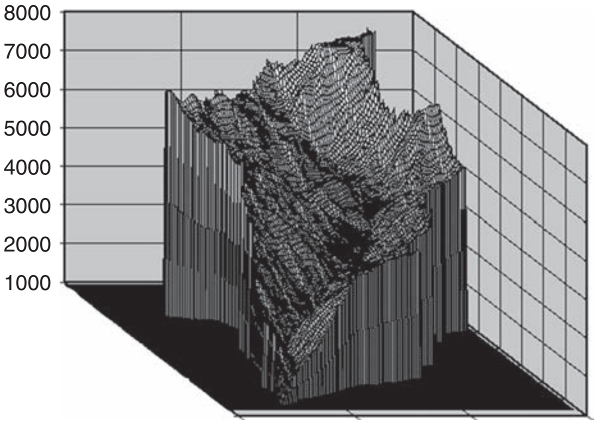


Figure 10 Raikot Basin 2 ½ dimensional terrain image. The land cover ranges from permanent snow and ice at higher elevations to vegetation and non-vegetation at subsequent lower elevations.

science would be helpful. Issues of scale [160] and data uncertainty will continue to permeate many of these areas.

Geocomputation topics through which advancements would benefit GIS and watershed models sometimes overlap with those listed under the structure of GIScience, for example in the areas of machine learning and ANN, fuzzy logic [151], ABM, Web-GIS, data mining [58], cloud computing, and open-source GIS [16]. One of the identifying characteristics of geocomputation is the innovative spirit with which scientists pursue spatial analysis research and the imagination they bring free from traditional subject boundaries [58]. Their research is often undertaken outside the confines of canned software programs using computer programming [161]. Innovative areas to investigate include, "capturing emotional and belief-centered relationships between society and space [58, p. 167, 613] and multi-dimensional watershed representations."

Emerging sources of data will also enhance the evolution of GIS and watershed models. Denser sources of LiDAR data such Geiger LiDAR, and the extremely high density and high temporal sampling of SfM generated point cloud data obtained from a UAS will improve terrain representations, and the 3-D characterization of watersheds [163]. Fusing of these data sources may become more commonplace in the future [164]. Additional sensors (e.g. LiDAR and hyperspectral imagery) are also being flown on UAS platforms. Increasing amounts of data are becoming available through the general public including citizen science and VGI.

In terms of making the integration of GIS and watershed models more accessible applications have been developed through the WWW and using GIS (Web-GIS). These applications normally do not provide the full functionality of a GIS or watershed model, but they do provide capabilities to a wider range of users. Example analyses that can be undertaken include hydrograph evaluation [165] and the derivation of HRUs [166]. Supported by cyberinfrastructure, applications have been developed for improving access to hydrologic data (e.g. through the Consortium of Universities for the Advancement of Hydrologic Science, Inc., Hydrologic Information System), and can include analyses and visualization capabilities [167]. Web-based watershed management applications including the use of SDSS have been available [168, 169].

This article initially concentrated on the linkage between GIS and hydrologic models for watershed characterization and modeling. As indicated by Li et al. [93], however, after focusing on hydrologic processes perhaps the next evolutionary trend is to attempt to represent the water–land–air–plant–human nexus in watersheds along with the capability for decision support. Future watershed management efforts will involve the latest science and technologies, along with local knowledge and stakeholder input [5]. Social and ecological needs should be considered in addition to issues associated with climate change [5]. As watershed models evolve GIS and geospatial theory and technologies are positioned to make significant contributions to watershed characterization, modeling, and management.

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Abstract

The protection and effective management of watersheds is critical in order to preserve water quality and healthy ecosystems and to provide ecosystems services. The importance of incorporating the spatial dimension of watershed features and processes in watershed models has long been recognized. Geographic information systems (GIS) provide capabilities to characterize, visualize, and analyze the spatial nature of watersheds. The integration of GIS and watershed models provide a powerful combination for analyzing spatiotemporal watershed processes and supporting watershed management. The purpose of this article is to provide a foundation for understanding GIS as applied to watershed characterization and modeling, in particular, for hydrologic modeling. This article discusses the co-evolution of GIS and hydrologic modeling and their eventual integration. GIS topics include data models, data acquisition, metadata, georeferencing, fundamental thematic data layers, and issues of scale and data uncertainty. Forms of integration for GIS and hydrologic models are outlined and the range of applications of GIS and watershed models is presented. In addition, areas in which potential advancements may emerge are considered including the fields of geographic information science (GIScience) and geocomputation, new data sources, Web-GIS, and integrated watershed management.

Keywords

GIS; watershed; hydrologic modeling; GIScience; geocomputation