7

GIS and Remote Sensing Applications in Modern Water Resources Engineering

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CONTENTS

Abstract Geographic information system (GIS) and remote sensing (RS) concepts and technologies are used extensively in modern water resources engineering planning, design, and operations practice and are changing the way these activities are accomplished. GIS has become an increasingly important means for understanding and dealing with the pressing problems of water and related resources management in our world. GIS concepts and technologies help us collect and organize the data about such problems and understand their spatial relationships. GIS analysis capabilities provide ways for modeling and synthesizing information that contribute to supporting decisions for resource management across a large range of scales, from local to global. And GIS provides a means for visualizing resource characteristics and thereby enhancing understanding in support of decision-making. This chapter introduces GIS and RS and their application to water resources systems. A general overview of GIS is presented which is followed by summary review of GIS applications for modern water resources engineering.

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SELECTED ABBREVIATIONS

ABR	Average basin rainfall
AMBER	Areal mean basin effective rainfall
API	Application program interface
ALERT	Automated local evaluation in real time
AML	Arc macro language
AMSR	Advanced Microwave Scanning Radiometer
CAD	Computer-aided design
CAPPI	Constant altitude plan position indicator
CASE	Computer-aided software engineering
CDSS	Colorado Decision Support System
CERL	Construction Engineering Research Lab (US Army Corps of Engineers)
CRWR	Center for Research in Water Resources (Univ. Texas, Austin)
CU	Consumptive use
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science
CWCB	Colorado Water Conservation Board
DBMS	Database management system
DCIA	Directly connected impervious area
DCP	Data collection platform
DCS	Data Capture Standards (FEMA)
DEM	Digital elevation model
DFIRM	Digital flood insurance rate map
DLG	Digital line graph
DMI	Data management interface
DOQQ	Digital Orthoimagery Quarter Quadrangles
DPA	Digital precipitation array
DSS	Decision Support System
DTM	Digital terrain model
EDNA	Elevation derivatives for national applications
EOS	Earth observation satellite
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute, Inc.
ET	Evapotranspiration
ETM+	Enhanced Thematic Mapper Plus
F2D	Flood two-dimensional rainfall-runoff model

FDA	Flood damage analysis
FEMA	Federal Emergency Management Agency
FFG	Flash flood guidance
FIRM	Flood insurance rate map
FIS	Flood Insurance Studies
FWPP	Flood warning and preparedness program
Geo-MODSIM	GIS-based MODSIM (Modular Simulation program)
GeoRAS	Geospatial River Analysis System
GIS	Geographical Information System
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GNIS	Geographic Names Information System
GOES	Geostationary operational environmental satellite
GPS	Global positioning system
GRASS	Geographic Resources Analysis Support System
GUI	Graphical user interface
HAS	Hydrologic analysis and support
HEC	Hydrologic Engineering Center (US Army Corps of Engineers)
HEC-RAS	HEC River Analysis System
HIS	Hydrologic Information System
HL-RMS	Hydrology Lab—Research Modeling System (NWS)
HMS	Hydrologic Modeling System (HEC)
HMT	Hydrometeorological Testbed (NOAA)
HRAP	Hydrologic Rainfall Analysis Project
HTML	Hypertext markup language
HTTP	Hypertext transfer protocol
HUC	Hydrologic unit code
LIDAR	LIght detection and ranging
LSM	Land Surface Model
LULC	Land use–land cover
MAP	Mean areal precipitation
MD	Maximum day demand
MH	Maximum hour demand
MODFLOW	Modular Finite-Difference Groundwater Flow Model
MPE	Multisensor precipitation estimator
MRLC	Multi-resolution Land Characteristics Consortium
MSS	Multispectral scanner
NAIP	National Agricultural Imagery Program
NASA	National Aeronautics and Space Administration (USA)
NASIS	National Soil Information System
NDVI	Normalized Difference Vegetation Index
NED	National Elevation Dataset
NFIP	National Flood Insurance Program
NESDIS	National Environmental Satellite Data Information Service

NEXRAD	Next Generation Weather Radar
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NLDAS	North American Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRCS	Natural Resources Conservation Service
NRC	National Research Council
NSA	National Snow Analyses
NWS	National Weather Service
NWIS	National Water Information System (USGS)
OSD	Official Soil Series Description
PDSI	Palmer Drought Severity Index
PPS	Precipitation processing system (radar)
PRISM	Parameter-Elevation Regressions on Slope Model
QPE	Quantitative precipitation estimate
QPF	Quantitative precipitation forecast
RDBMS	Relational Database Management System
RFC	River Forecast Center (NWS)
RGDSS	Rio Grande Decision Support System
SAC-SMA	Sacramento Soil Moisture Accounting
SCADA	Supervisory Control and Data Acquisition
SDMS	Spatial Data Management System
SDSS	Spatial Decision Support Systems
SLAR	Side-Looking Airborne Radar
SMA	Soil Moisture Accounting
SQL	Structured Query Language
SSM/I	Special Sensor Microwave/Imager
SSURGO	Soil Survey Geographic Database
STATSCO	State Soil Geographic Database
STORET	STOrage and RETrieval
STP	Storm total precipitation
TIGER	Topologically Integrated Geographic Encoding and Referencing
TIN	Triangulated Irregular Network
TM	Thematic Mapper
UH	Unit hydrograph
UML	Universal Modeling Language
USBR	United States Bureau of Reclamation
USDA	US Department of Agriculture
USGS	United States Geologic Survey
UZFWM	Upper-zone free water maximum
WADISO	Water Distribution System Analysis and Optimization
WADSOP	Water Distribution System Optimization
XML	Extensible Markup Language

1. INTRODUCTION

Information about water resources and the environment is inherently geographic. Maps, whether on paper or in digital GIS formats, continue to be the medium for expression of engineering plans and designs. We are concerned about the spatial distribution and character of the land and its waters. Weather patterns, rainfall and other precipitation, and resultant water runoff are primary driving forces for land development, water supplies, and environmental impacts and pollution. Our water resources systems are comprised of dams and reservoirs, irrigated lands and canals, water supply collection and distribution systems, sewers and stormwater systems, and floodplains. These systems are tailored in response to a complex mix of topography and drainage patterns, population and land use, sources of water, and related environmental factors.

A geographic information system (GIS) presents information in the form of maps and feature symbols and is integrated with databases containing attribute data on the features. A GIS is a computer-based information system that supports capture, manipulation, retrieval, modeling, analysis, and presentation of spatial data. This is a standard definition that does not highlight the uses of GIS as an integrator of data management operations and decision support in an organization. Looking at a GIS map gives knowledge of where things are, what they are, and how they are related. A GIS can also provide tabular reports on the map features, create a list of all things connected in a network, and support simulations of river flows, travel time, or dispersal of pollutants. A more expansive view is that the purpose of a GIS is to provide a framework to support decisions for the intelligent use of earth's resources and to manage the built and natural environment. Purposes and concepts of GIS are a key to the understanding and successful application of this technology.

A GIS provides an integrating data and modeling environment for the conduct of these activities. A GIS provides a means to collect and archive data on the environment. Measurements of location, distance, and flow by various devices are typically handled in digital formats and quickly integrated into a spatial database. Data processing, synthesis, and modeling activities can draw on these data using the GIS, and analysis results can be archived as well. The GIS spatial and attribute database can then be used to generate reports and maps, often interactively, to support decision-making on which alternatives are best and the impacts of these. Further, maps are a powerful communication medium; thus, this information can be presented in public forums so that citizens concerned with planning and design choices can better understand and be more involved.

Planning and design in water resources engineering typically involve the use of maps at various scales and the development of documents in map formats. For example, in a river basin study, the map scale often covers a portion of a state and includes several counties and other jurisdictions. The river drains a certain geography having topographic, geologic and soil, vegetation, and hydrological characteristics. Cities and human-built facilities are located along the river and across the basin, and transportation and pipeline networks link these together. It is required that all of these datasets be established in a common geo-reference framework so that overlays of themes can be made and the coincidence of features identified in the planning and design phase.

A GIS is applied to manage all of these data. It provides a comprehensive means for handling the data that could not be accomplished manually. The large amount of data involved requires a GIS—there may be many thousands of features having a location, associated attributes, and relationships with other features. The GIS provides a means to capture and archive these data and to browse and review the data in color-coded map formats. This data review capability supports quality control as errors can be more readily identified. Also, through visualization, the user can gain a better understanding of patterns and trends in the data in a manner not possible if the data were only in tabular format. The GIS provides an analysis capability as well; new information can be obtained by the wide variety of spatial analysis functions and linked mathematical models. The database can be accessed by the computer software and used as input to various modeling procedures to generate derived products.

A comprehensive review of GIS for water resources engineering was presented by Johnson [1]. That book addressed fundamental concepts of GIS database development and applications of GIS for surface and groundwater hydrology, flood plains, water supply and wastewater systems, water quality, and river basin decision support systems. This chapter presents a summary review of GIS concepts and water resources engineering applications. It is intended to inform the reader on the role that GIS plays in modern water resources engineering in concert with the other topics presented in this book.

2. OVERVIEW OF GEOGRAPHIC INFORMATION SYSTEMS AND REMOTE SENSING

2.1. GIS Basics

GIS concepts and technologies arise from a wide variety of fields, and GIS has become a generic term referring to all automated systems used primarily for the management of maps and geographic data. The development of GIS has relied on innovations made in many disciplines: civil engineering, geography, photogrammetry, remote sensing, surveying, geodesy, statistics, computer science, operations research, demography, and many other branches of engineering and the natural and social sciences. Indeed, an outstanding characteristic of GIS is its interdisciplinary character in its development as a collection of tools as well as the wide variety of applications.

GIS cartographic concepts originated with the maps created by early explorers and extended by modern geographers to portray locations and characteristics of the earth's features. Engineering measurement theories and practices of surveyors and geodesists provided the means to describe property boundaries and locate features accurately. Civil engineers have migrated to digital formats for land development plans which include parcel boundaries as well as elements for water and sewer pipes, roads and streets, and other infrastructure. Satellite and airborne remote sensing technologies have advanced to become a primary data source for high-resolution mapping of land characteristics; these apply for base mapping, in real time, and for assessing changes over time.

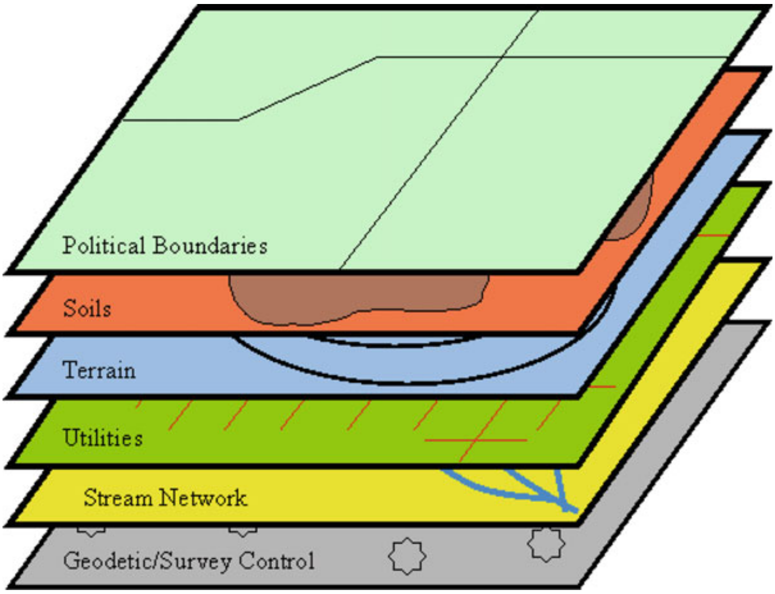

Fig. 7.1. Map layers address multiple themes.

It has become common to think of GIS databases as a collection of map layers that are geographically referenced and registered to a common coordinate projection. Most GIS organizes data by layers, each of which contains a theme of map information that is logically related by its location (Fig. 7.1). Each of these separate thematic maps is referred to as a layer, coverage, or feature dataset. And each layer has been precisely overlaid on the others so that every location is matched to its corresponding locations on all the other maps. The geodetic control layer of this diagram is quite important; it represents the coordinate location reference system to which all the maps have been accurately registered. Once these maps have been registered within a standardized reference system, information displayed on the different layers can be compared and analyzed in combination.

2.2. *GIS Data Development and Maintenance*

Input or capture of data comes from a variety of sources. The data may be converted from existing paper (or mylar) plans and records, as well as data residing in digital databases (e.g., property records). These conversions may involve tablet digitizing and scanning to images. Over the past several decades, there has been a convergence of GIS with the technologies of engineering measurement that record field data in digital formats and can be ported directly into a GIS spatial database (e.g., surveying total stations and global positioning systems (GPS)). Data capture technologies include remote sensing by satellites and airborne platforms (photogrammetry). Satellite imagery is received in various wavelengths so that particular aspects of the land surface can be characterized through image processing procedures. Imagery from airplane overflights is most often of the photographic type, particularly for development of high-resolution topographic maps of urban areas and identification of urban features such as building footprints, street centerlines, manholes, and water distribution valves. Increasingly, Light Detection and Ranging (LIDAR) is being used to provide high-resolution topographic mapping required for detailed site planning and floodplain hydraulic studies. Regardless of the source, there is a requirement that spatial data be developed in some coordinate reference system.

GIS functions for spatial data capture include the numerous technologies for data capture as well as the many ways for conversion of source data into GIS compatible formats. These functions include:

- Tablet digitizing and scanning
- Format conversion
- Surveying and coordinate geometry (COGO)
- Global positioning systems
- Photogrammetric data development
- Image processing
- Geometric transformations and projection conversions
- Attribute entry and editing
- Metadata

2.3. *Remote Sensing*

Satellite remote sensing can provide various sources of data for water resources applications ranging from basic land use characteristics (and changes over time) to terrain and to meteorological event tracking. Satellites using the visible and near-infrared regions of the spectrum can provide detailed information of the land characteristics, and SPOT with its stereo capability can even provide topographic information [2]. Side-Looking Airborne Radar (SLAR) and satellite SLARs can produce vary detailed maps of basin characteristics, even in traditionally cloudy areas and areas with heavy vegetation growth. Interferometric SLAR can also provide quantitative measures of topography.

Image processing functions have been developed to extract information from satellite imagery, although many of the procedures may be applied to other grid datasets as well. Jensen [3] describes image processing functions and techniques in some detail. Image classification is accomplished using multispectral classification methods that transform raw reflectivity data into information on land cover classes. There are a variety of classification algorithms including (1) hard classification using supervised or unsupervised approaches, classification using fuzzy logic, and/or (2) hybrid approaches using ancillary (collateral) information. Supervised classification involves a priori identification and location of land cover types, such as urban, agriculture, or wetland, through a combination of field work, aerial photography, and other mapping. Specific sites, called training sites, having known spectral characteristics are located in the image and are used to train the classification algorithm for application to the remainder of the image. This is a hard classification scheme since each pixel is assigned to only one class. In unsupervised classification, the identities of land cover types are not known a priori, and training site

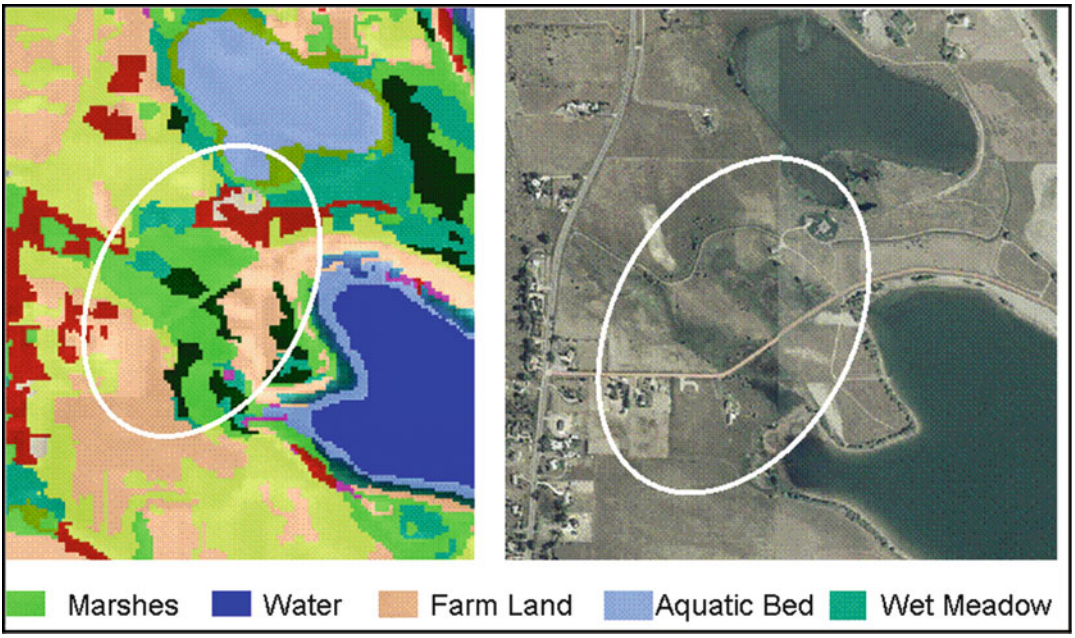

Fig. 7.2. Image processing techniques are used to classify land characteristics. Example shown identifies wetland areas in mixed agricultural landscape [4].

data are not collected or are unavailable. Figure 7.2 illustrates an example of image classification for wetland identification.

2.4. GIS Data Models and Geodatabases

GIS databases incorporate two distinct branches: the spatial database and the associated attribute database. Many GIS software maintain this distinction; the spatial data is characterized as having a "vector" structure comprised of features represented as points, lines, and polygons. Other GIS spatial data are handled as images, or "rasters," having simple row and column formats. Figure 7.3 illustrates the difference between the raster and vector data structures. Attribute data are handled in relational database software comprised of records and fields, and the power of the relational model is applied for these data. These feature data are "tagged" to the spatial database to facilitate tabular data retrievals.

Database management systems (DBMS) are computer programs for storing and managing large amounts of data. Required functions of a DBMS include (1) consistency with little or no redundancy, (2) maintenance of data quality including updating, (3) self-descriptive with metadata, (4) a database language for query retrievals and report generation, (5) security including access control, and (6) shareable between users. Most DBMS are designed to handle attribute data. A special characteristic of a geodatabase is the join between spatial and attribute data for water resources system features.

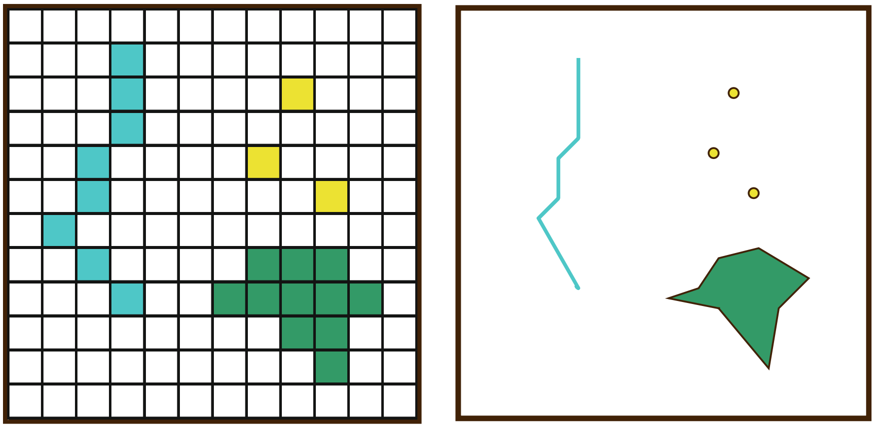

Fig. 7.3. Raster (grid) and vector data structures provide complementary means for representing location and character of map features.

2.5. *GIS Analysis Functions*

GIS analysis capabilities are specifically keyed to the spatial realm. An analysis function unique to GIS is the overlay operation whereby multiple data themes can be overlain and the incidence of line and polygon intersections are derived. This graphical and logical procedure is used in many ways to identify the correspondence between multiple data layers. Other GIS functions include networks and connectivity operations, terrain analyses, statistical interpolation, and other neighborhood procedures, as well as functions for spatial database development and maintenance.

The nature of the data representation has a strong influence on the analysis that can be applied. Spatial data in GIS are most often organized into vector and raster (or surface) data structures (Fig. 7.3). In the vector structure, geographic features or objects are represented by points, lines, and polygons that are precisely positioned in a continuous map space, similar to traditional hard copy maps that identify landmarks, buildings, roads, streams, water bodies, and other features by points, lines, and shaded areas. In addition, each object in the vector structure includes topologic information that describes its spatial relation to neighboring objects, in particular its connectivity and adjacency. This explicit and unambiguous definition of and linkage between objects makes vector structures attractive and allows for the automated analysis and interpretation of spatial data in GIS environments [5].

On the other hand, surface, or raster (from display technology), data structures divide space into a two-dimensional grid of cells where each cell contains a value representing the attribute being mapped. A raster is an x, y matrix of spatially ordered numbers. Each grid cell is referenced by a row and column number with the boundary of the grid being registered in space to known coordinates. Raster structures arise from imaging sources such as satellite imagery and assume that the geographical space can be treated as though it was a flat Cartesian surface [6]. A point is represented by a single grid cell, a line by a string of connected cells and an area by a group of adjacent cells. When different attributes are considered such as soil and land use, each is represented by separate raster layers. Operations on multiple layers involve the retrieval and processing of the data from corresponding cell positions in the different layers. This overlay concept is like stacking layers (two-dimensional grids) and then analyzing each cell location [5]. The simplicity of data processing in raster structures has contributed to its popularity. Both vector and raster structures are valid representations of spatial data. The complementary characteristics of both structures have long been recognized, and modern GIS can process both structures, including conversion between structures and overlays of both structures.

GIS provides a rich suite of intrinsic functions that perform analyses using attributes of spatial data. In many respects, these intrinsic functions provide unprecedented capabilities (i. e., no historical manual equivalent) that are difficult and time consuming if performed manually. Terrain processing for watershed delineation is but one example of GIS functions that can be conducted much easier and better than can be done manually. As will be shown in subsequent chapters, the range and sophistication of spatial analyses applied to water resources problems are extensive. Moreover, integration of conventional water resources analysis procedures into the GIS sphere has extended the realm of GIS to include advanced surface modeling, simulation, and optimization functions heretofore not often recognized by GIS practitioners. Also, the water resources field now includes a wide range of decision support systems for planning and operations that involve a dominant spatial dimension; these are called spatial decision support systems (SDSS).

The art and science of using a GIS entails combining the available analysis functions with the appropriate data to generate the desired information. GIS practice therefore requires some schema of design to ensure that the effort is focused on answering the appropriate questions. Here, the GIS database, modeling, and visualization tools provide enhancements to the traditional engineering design process. The GIS provides a powerful means to manage data, conduct analyses, and communicate planning and design outcomes to the various "publics" concerned with these outcomes. This communication dimension of GIS is particularly important in environmental and water resources engineering because much of our work concerns public resources having significant impacts over extensive areas on a large number of interest groups.

General categories of analysis functions include the following:

1. Data capture and maintenance
2. Geometrics and measurements
3. Spatial and aspatial queries; classifications
4. Neighborhood operations
5. Spatial arrangement, connectivity functions, and networks
6. Surface operations
7. Overlays and map algebra
8. Spatial statistics
9. Display, interfaces, integration
10. Management models

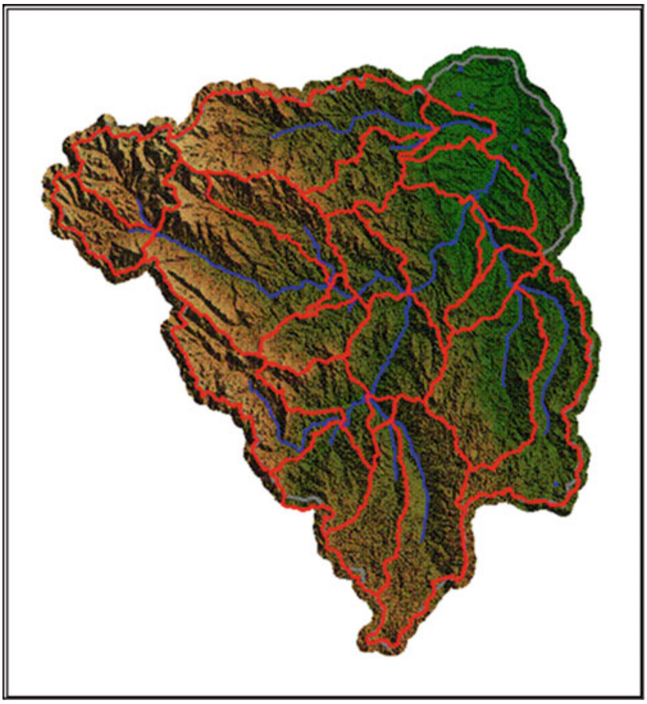

Fig. 7.4. DEM processing routines are applied to extract stream networks and watershed.

Automated extraction of watersheds or surface drainage, channel networks, drainage divides, and other hydrographic features from DEMs is a standard surface processing routine in modern GIS (Fig. 7.4). The eight-direction, or D-8, method is the most common approach to identifying the direction of flow from a grid cell. Using an iterative approach similar to the spread and seek functions, the D-8 defines the drainage network from raster DEMs based on an overland flow analogue. The method identifies the steepest downslope flow path between each cell of a raster DEM and its eight neighbors and defines this path as the only flow path leaving the raster cell. The method also accumulates the catchment area downslope along the flow paths connecting adjacent cells. The drainage network is identified by selecting a threshold catchment area at the bottom of which a source channel originates and classifying all cells with a greater catchment area as part of the drainage network. This drainage network identification approach is simple and directly generates connected networks.

2.6. User Interfaces and Interaction Modes

A primary attraction of modern GIS is the user-friendliness of the computer system interface provided by the various software vendors. Efficient retrieval of data depends not only on properly structured data in the database and speed of retrieval but also on well-designed interfaces and query languages. The human–computer interface provides the environment that enhances human interaction with the GIS. It makes it easy for the user to access data and analysis results and to display these data in understandable formats. Most traditional information systems provide limited presentation formats, usually as text, tables, and graphs. While these formats are still useful, the spatial character of geodata allows additional possibilities, including map formats and visualization techniques.

To achieve usability, GIS software has progressed from command entry modes to menu and forms modes to graphical user interfaces (GUI) [7]. A GUI enables a user to interact with the computer system by pointing to pictorial representations (icons) and lists of menu items on the screen using the mouse. Using the icons provides a means for the primary functionality of data selection, data presentation, and data manipulation.

Visualization is an extension of the traditional data retrieval and display concepts. It includes techniques that aid in the interpretation of spatial datasets. Since GIS is concerned with analysis and interpretation, it is the graphics-based nature of GIS that allows perception of spatial patterns and features of the information, extraction of parameters, and discrimination of classes of objects [8].

2.7. GIS System Planning and Implementation

Consideration of organizational factors is important to successful GIS implementation and management because of the critical role that information plays in an organization's role and purpose. In most cases, the design and implementation of a GIS and is a long-term effort that involves changes in the way an organization does its work. Experience has shown that, as important as technical issues of software, hardware, and database design are, it is the people problems arising from access to the information and its use that determine whether a GIS will succeed or fail [9].

During the planning of a major GIS acquisition and/or development, it is important to consider certain organizational attributes that will impact the chosen approach. These attributes, generally addressed in a Needs Assessment, should be evaluated in the broadest possible sense. In this way, the goals, equipment, costs, etc., of all impacted departments will be included in the implementation planning. Only after careful consideration of these attributes can the best possible implementation strategy be chosen. Some attributes to consider:

- Overall organization function and goals.
- Sources of data available as input to the GIS system.
- GIS hardware/software/databases and products that are currently and planned to be utilized.
- Management approaches that will guide and have guided the GIS program to date.
- Costs of implementation, both historic and planned.
- Benefits of implementation, both tangible and intangible.
- Procedure to be used in evaluating and comparing the costs and benefits.
- Review generation procedures: internal, external, current, and potential.
- Quality Assurance/Quality Control Procedures (QA/QC) and any applicable data standards.
- End-user interactions and training consider how the GIS group will communicate with its "clients."
- Evaluation/assessment procedures to be used to review the GIS implementation.
- Legal issues pertaining to data distribution and ownership.

Although it is difficult to quantify many of these attributes, it is a useful exercise to at least estimate the worth of each one. For instance, many organizations consider a formal cost/benefit analysis to be based on highly speculative information, although it is possible to measure the relative "goodness" of intangible benefits on a relative scale. Further, as these types of organizational issues are discussed during planning, a broader and more realistic picture of the resulting GIS implementation becomes available.

2.8. GIS Software

There are a large number of GIS software options which are available as open source or commercial products. A large listing of GIS software can be found at: http://en.wikipedia.org/wiki/GIS_software.

3. GIS FOR SURFACE WATER HYDROLOGY

3.1. GIS Data for Surface Water Hydrology

The watershed runoff processes are inherently spatial in character so there is a strong motivation to use GIS tools to organize the data and formulate hydrologic models. Surface water hydrology is perhaps the area for which GIS has been most applied in the water resources and environmental field. The advent of digital data products and software for processing spatial data has prompted a change in the way we look at hydrologic systems and made it possible to more precisely describe watershed characteristics and runoff response to precipitation inputs. There is a movement away from the so-called "lumped parameter" models to more spatially distinct or "distributed" modeling approaches that represent fundamental physical processes.

The general availability of DEMs, TINs, DLGs, digital soil and land use data, radar-rainfall and satellite imagery, real-time gage reporting, and the GIS software to process these has contributed to an increased awareness of the spatial distribution of hydrologic processes. Most surface water hydrologic applications begin with raster data of the terrain due to the wide availability of DEMs and intrinsic GIS software functions to conduct digital terrain processing. For highly detailed terrain mapping, such as required to define floodplain details, there is increasingly wide use of Light Detection and Ranging (LIDAR) data.

Hydrographic vector data of surface water systems are also common and may have been developed as features in the original map making process or derived from DEM processing. A primary dataset on stream vectors is the National Hydrography Dataset (NHD; Fig. 7.5). The NHD is designed to combine spatial accuracy with detailed features, attributes, and values to provide information on flow paths, permanent reach IDs, and hydrologic ordering for use in modeling [10].

Soil data are available from the soil-mapping agencies, typically those dealing with the agriculture sector. In the USA, soil survey data are available in digital formats from the Natural Resources Conservation Service (NRCS), including the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) databases. The mapping scale for

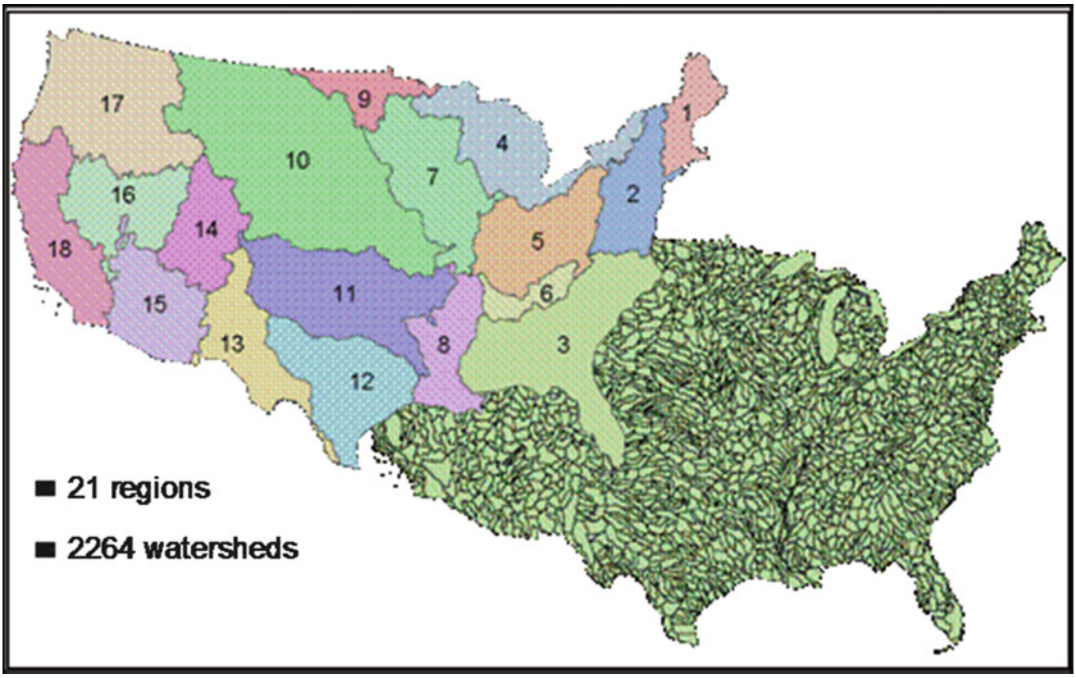

Fig. 7.5. NHD watersheds are organized in a hierarchical manner for the various levels of scale [11].

STATSGO map is 1:250,000 and was created by generalizing more detailed soil survey maps. The SSURGO digitizing duplicates the original soil survey maps at mapping scales ranging from 1:12,000 to 1:63,360. SSURGO is linked to the National Soil Information System (NASIS) attribute database. The attribute database gives the proportionate extent of the component soils and their properties for each map unit. Recent advances in remote sensing technology have shown that soil moisture can be quantitatively estimated using microwave technology under a variety of topographic and vegetation cover conditions. A summary assessment of the state of the art of remote sensing of soil moisture was presented by the National Research Council [11].

Land use and land cover information is used in hydrologic modeling to estimate surface roughness or friction values since it affects the velocity of the overland flow of water. Sources of land use data include the USGS-EPA National Land Cover Dataset (NLCD) which has been developed with time stamps for 1992 and 2001 and is appropriate for most watersheds modeling (Fig. 7.6). The most recent release includes an impervious surface coverage. Interpretation of land use information from satellite imagery or aerial photography is another means of obtaining land use and land cover data. The techniques of supervised and unsupervised classification of satellite imagery yield clusters of different spectral classes that are assigned into different land use types. The same technique can be used with aerial photos that are digitally scanned. Research by Ragan and Jackson [12] and Bondelid et al. [13] has shown that the degree of urban land use or various categories of agriculture or forest can

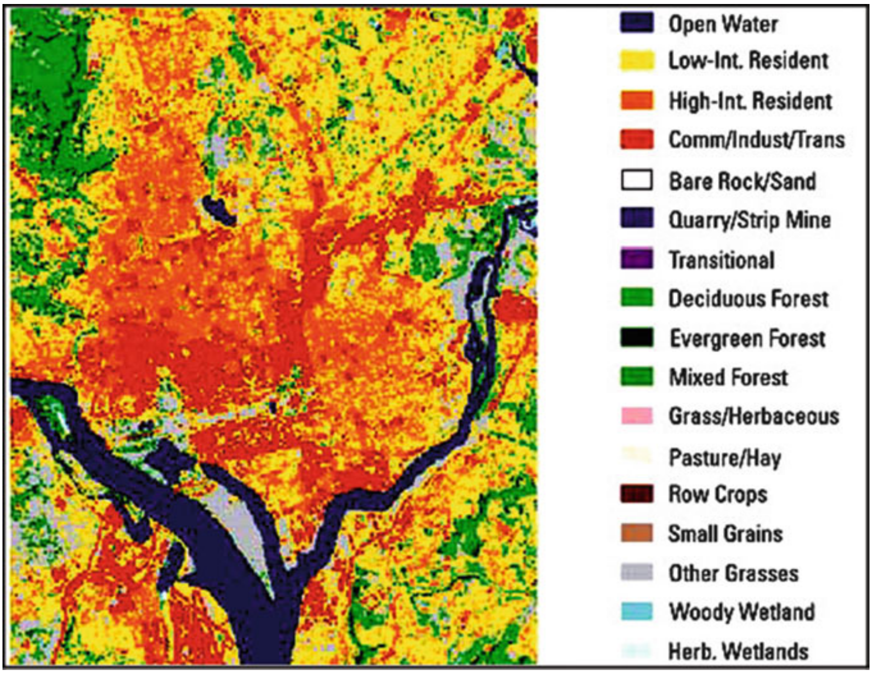

Fig. 7.6. National Land Cover Dataset is available nationwide and is widely used for watershed modeling studies.

be determined accurately through remote sensing and used as variables in urban runoff models or the SCS runoff curve number method.

Precipitation and climate data of various types are routinely collected by the National Weather Service, other agencies, and citizen volunteers at specific locations. The primary data archive for climate and other meteorological data is the National Climatic Data Center (NCDC). Land-based observations archived by the NCDC contain various meteorological elements that over time describe the climate of a location or region. These elements include temperature, dew point, relative humidity, precipitation, snowfall, snow depth, wind speed, wind direction, cloudiness, visibility, atmospheric pressure, evaporation, and soil temperatures.

Weather radars have become a primary source of rainfall data (Fig. 7.7). Weather radar data are available from the National Weather Service (NWS) Weather Surveillance Radar Doppler units (WSR-88D) throughout the USA. The WSR-88D radar transmits horizontal pulses, which give a measure of the horizontal dimension of the cloud (cloud water and cloud ice) and precipitation (snow, ice pellets, hail and rain particles). Over a 5- to 10-min period, successive scans are made with 0.5° increments in elevation. The reflectivity observations from these scans are integrated over time and space to yield estimates of particle size and density in an atmospheric column over a particular location. To simplify data management, display, and analysis, the NWS digitizes and reports reflectivity for cells in a Hydrologic Rainfall Analysis Project (HRAP) grid. Cells of the grid are approximately 4 km by 4 km.

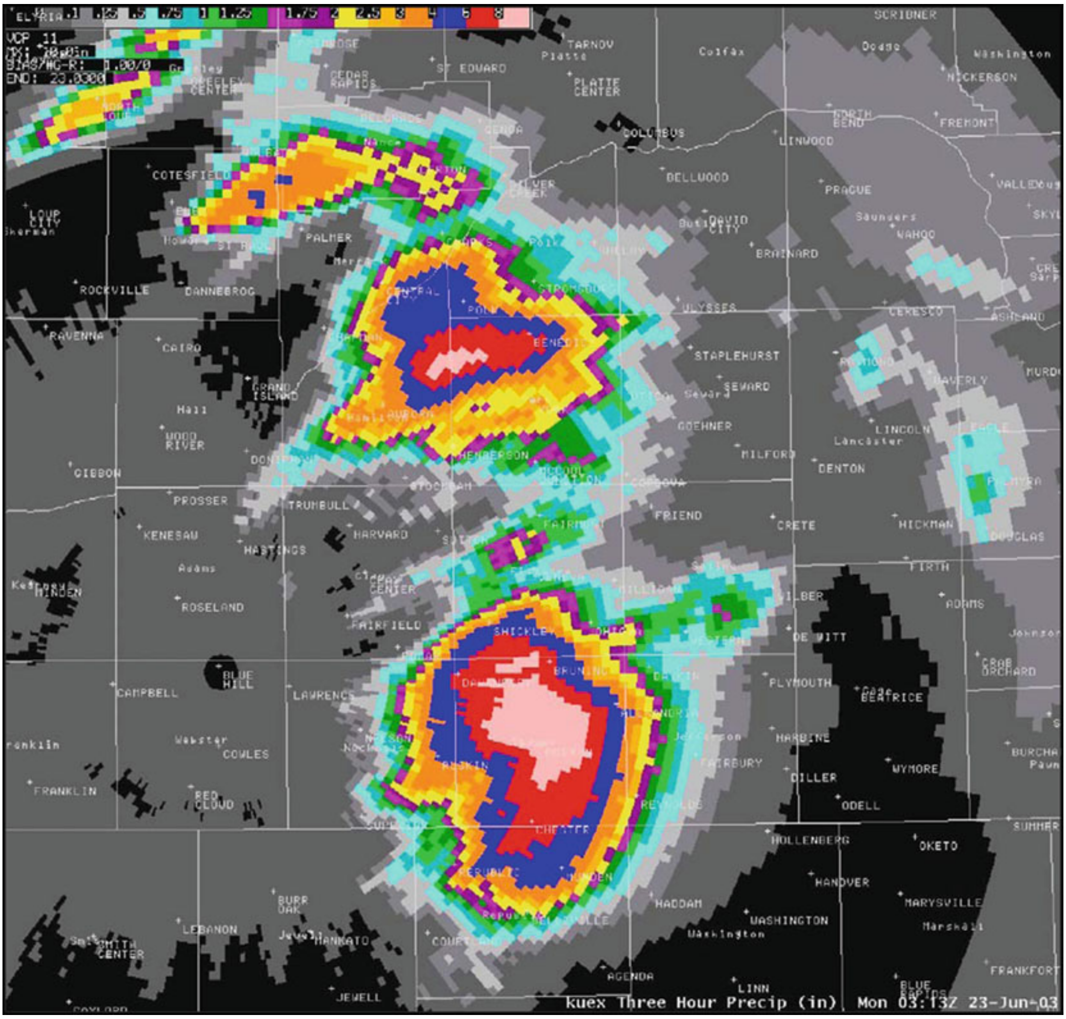

Fig. 7.7. Radar-rainfall data are being collected nationwide by the WSR-88D system. Image displays example of 3-h rainfall accumulation product [14].

Satellite imagery can provide useful information on rainfall distribution over large areas and inaccessible regions. However, direct measurement of rainfall from satellites for operational purposes has not been generally feasible because the presence of clouds prevents direct observation of precipitation with visible, near-infrared, and thermal infrared sensors. The visible and infrared images from the polar-orbiting satellites, including the NOAA N series and the Defense Meteorological Satellite Program, and geostationary satellites such as GOES, GMS, and Meteosat provide information only about the cloud tops rather than cloud bases or interiors. These satellites provide frequent observations (even at night with thermal sensors), and the characteristics of potentially precipitating clouds and the rates of changes in cloud area and shape can be observed. From these observations, estimates of rainfall can be made which relate cloud characteristics to instantaneous rainfall rates and cumulative rainfall over time. Improved analysis of rainfall can be achieved by combining satellite and conventional gage data.

Snow is another hydrologic variable that has been successfully measured for large regions using aerial and satellite remote sensors. Ground-based snow surveys are also routinely collected at sites by the Natural Resources Conservation Service (NRCS). The National Operational Hydrologic Remote Sensing Center (NOHRSC) ingests daily ground-based, airborne, and satellite snow observations from all available electronic sources for the coterminous USA. These data are used along with estimates of snowpack characteristics generated by a physically based snow model to generate the operational, daily NOAA National Snow Analyses (NSA) for the coterminous USA. Extent of snow cover can be determined with satellite visible and near-infrared (VIS/NIR) data and can be observed in remote regions that are generally inaccessible during the winter months.

3.2. GIS for Surface Water Hydrology Modeling

GIS analysis and database functions provide extensive means for developing surface water hydrologic models datasets and modeling operations. A primary area of application is processing of digital terrain data to derive landscape features pertinent to hydrology such stream paths and drainage divides. GIS databases are created to help organize the multitude of spatial and nonspatial attribute data needed for surface water hydrologic studies. Intrinsic GIS surface and network analysis functions provide fundamental capabilities for deriving surface water modeling products.

Digital representations of landscape topography as digital elevation models (DEM) or digital terrain models (DTM) incorporate arrays of elevation values so that terrain features can be evaluated using specialized numerical algorithms and GIS visualizations rendered. Landscape features such as slope, aspect, flow length, contributing areas, drainage divides, and channel network can be rapidly and reliably determined from DEMs even for large watersheds [15]. A concise review of digital terrain processing methods was presented in DeBarry [16]. Automated extraction of surface drainage, channel networks, drainage divides, drainage networks and associated topologic information, and other hydrography data from DEMs has advanced considerably over the past decade and is now routinely a part of most GIS software packages.

The common problem of obtaining rainfall data for the watershed of interest using point rain gages is addressed using spatial interpolation procedures. Interpolation methods are appropriate when an attribute measured at sample points is a spatially continuous field variable. Usually, the interpolation process involves estimating the rainfall values onto a regular grid. Alternately, contours may be fitted to the grid and the data represented as vector objects with labels or as polygon objects having the contours as boundaries. The interpolated surface may also be represented as a TIN. There are a wide variety of procedures for interpolation and supporting literature (e.g., [17, 18]). For this discussion, five methods are described: (1) nearest neighbor, (2) isohyetal, (3) triangulation, (4) distance weighting, and

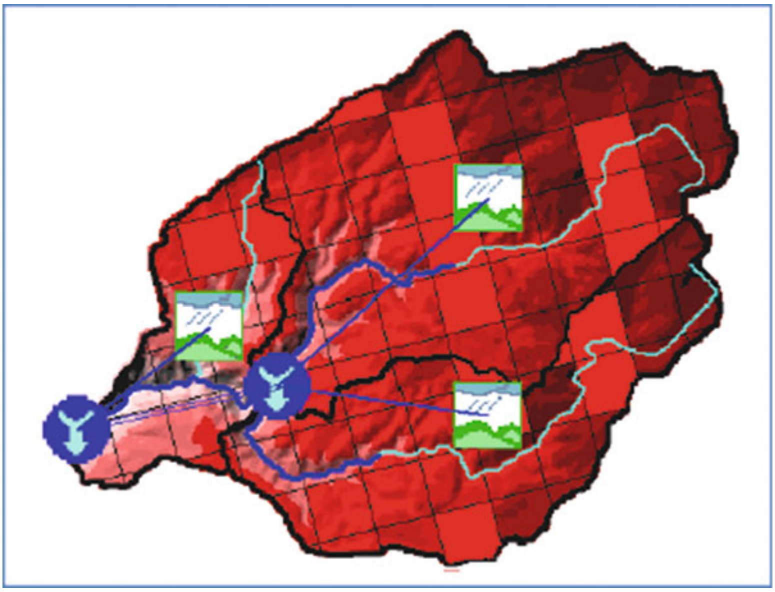

Fig. 7.8. HEC-GeoHMS provides an integrated GIS work environment for watershed modeling.

(5) kriging. A concern with interpolation with sparse network data is that different interpolation methods may yield differing results; an independent verification dataset is commonly used to determine the best method.

GIS procedures for computing evaporation and evapotranspiration (ET) include interpolation of the input meteorological data from weather stations to the location of interest. These spatial interpolations may be accomplished in a manner similar to those used for rain gage data. Computations may be accomplished using map algebra techniques for regular grid structures across the landscape taking account of differences in temperature, precipitation, elevation, soils, vegetative cover, and other variables as required.

Runoff is generated from excess precipitation that has not infiltrated or been stored on the land surface. This direct runoff is translated from its location on the ground to the nearest steam channel (overland flow) of to the watershed outlet. The unit hydrograph is a well-known, commonly used empirical model of the relationship of direct runoff to excess precipitation [18]. Various versions of the UH have been developed, including (1) user-specified UH and (2) Clark's UH, Snyder's UH, the SCS UH, and ModClark UH. These are options incorporated into the HEC-HMS software package (Fig. 7.8; [18]). The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS; [19]) is a software package for use with the ArcView® GIS. GeoHMS uses ArcView and Spatial Analyst to develop a number of hydrologic modeling inputs. Analyzing digital terrain information, HEC-GeoHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. In addition to the hydrologic data structure, capabilities include the development of grid-based data for linear quasi-distributed runoff transformation

Fig. 7.9. Watersheds with Pfafstetter index numbering [20].

(ModClark), the HEC-HMS basin model, physical watershed and stream characteristics, and a background map file.

Flow routing through the channel network is accomplished using a variety of mathematical representations of the fundamental equations of channel flow hydraulics. For example, The HEC-RAS system contains four one-dimensional river analysis components for (1) steady flow water surface profile computations, (2) unsteady flow simulation, (3) movable boundary sediment transport computations, and (4) water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines [18]. Regardless of the channel routing method, GIS representations of the network as a binary tree collection of reaches and junctions are central to coordinating the logical sequencing of computations from an upstream to downstream direction. The network database includes the topological relations to identify upstream and downstream nodes and junction characteristics. Sometimes the indexing code generated by the stream network derivation (e.g., Pfasseter code) is used to schedule the sequencing of computations (Fig. 7.9).

Increasing availability of high-resolution DEMs and land surface data provides a foundation for distributed models of the watershed. The ModClark time-area method mentioned above is an example of a semi-distributed model. Also, a large basin may be represented as a collection of sub-basins; the overall system representation can be considered distributed. For fully distributed models, the excess precipitation amounts computed for various locations in the watershed, usually on a grid structure, are routed overland and through channels to the basin outlet. The distributed approach allows flow predictions at many points internal to the watershed.

The NWS Research Modeling System (HL-RMS) is an example of a fully distributed approach [21]. The HL-RMS has been developed to support proof of concept research comparing distributed modeling approaches with the more traditional lumped models based on the UH. Some of the main features of the current HL-RMS are:

- Ingests gridded NEXRAD-based products.
- Basic modeling unit is the NEXRAD grid cell (~4 km).
- Rainfall-runoff calculations are done independently for each grid cell.
- Runoff is routed over hillslopes within a model cell.
- Channel routing is done from cell to cell.
- Rainfall-runoff calculations can be done using lumped or distributed rainfall and lumped or distributed parameters.
- Uses the Sacramento Soil Moisture Accounting Model (SAC-SMA).
- Uses the kinematic method for both hillslope and channel routing.
- Writes output parameter, state, or forcing grids that can be displayed in ArcView GIS.

In HL-RMS, the impervious, surface, and direct runoff components are routed over conceptual hillslopes within each NEXRAD cell to a conceptual channel. Because of the relatively large size of the 4-km model cells, the cells are subdivided into conceptual hillslopes to make overland flow distances physically realistic. A drainage density parameter in the model is used to subdivide a cell into equally sized overland flow planes. These hillslopes drain to a conceptual channel segment within the same cell. Cell-to-cell channel routing is done using flow direction networks like that illustrated in Fig. 7.10. Three parameters are defined in each cell for kinematic overland flow routing: hillslope slope, hillslope roughness, and drainage density. Representative hillslope slopes are estimated using DEM data (initially with 30-m DEM data for basin-scale applications and 400-m DEM data for regional-scale applications) by first computing the local slope of each DEM cell in the study domain using the Arc/Info slope function and then averaging all of the DEM cell slopes in each 4-km model cell. A kinematic routing scheme is applied for the channels; parameters are based on stage-discharge, channel cross section, and other geomorphic data.

There are a number of surface water hydrologic models having integrated GIS interfaces and databases. A large listing of hydrologic models can be found at the Hydrologic Modeling Inventory Website (http://hydrologicmodels.tamu.edu/).

The National Weather Service has developed various methods for assessing the threat of flash floods for local forecast regions. The AMBER algorithm was developed at the Pittsburgh NWS Forecast Office in the early 1990s. The AMBER program provides the field forecaster direct guidance for issuance of flash flood warnings. AMBER directly links WSR-88D radar-rainfall estimates with all defined watersheds, down to a 2-square mile area (3 sq. km). AMBER computes average basin rainfall (ABR) in each watershed for direct comparison with flash flood guidance or other thresholds set by the forecasters. AMBER also computes

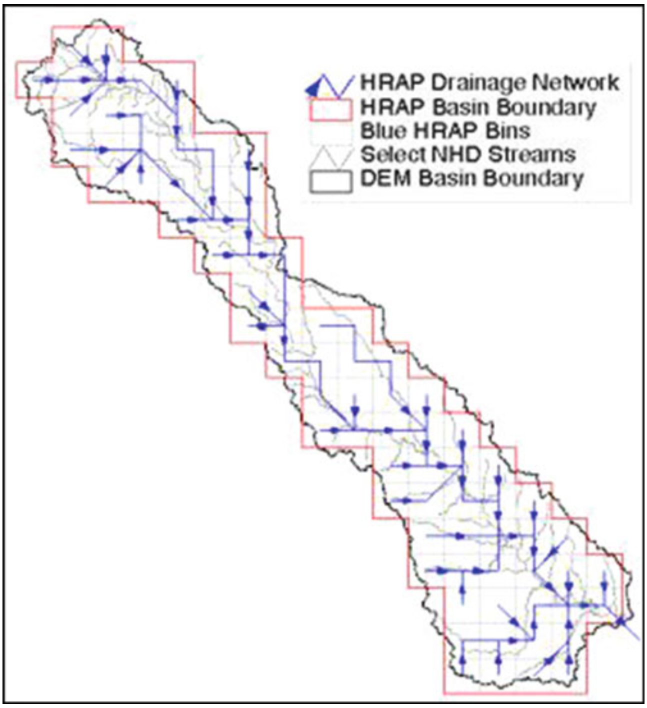

Fig. 7.10. HL-RMS distributed model represents conceptual hillslopes within a 4-km HRAP grid cell-to-cell drainage network [21].

the "rate" or intensity of each watershed ABR every 5–6 min. Scan-to-scan accumulation for all bins in a basin is summed using area of bin as weighting factor to compute ABR. The database saves the ABR for each basin for each scan-to-scan accumulation time period. Also, the ABR from scan-to-scan periods is summed to produce accumulation over longer time periods.

Basin delineations for AMBER were derived nationwide using GIS terrain processing procedures. A basin was defined for each segment of a stream network, and basins were defined for various thresholds of basin scale including (1) headwaters (e.g., less than 50 square miles); (2) streams (less than 200 square miles); (3) rivers (greater than 200 square miles); (4) urban areas, any area known to be prone to flooding; and (5) rain gages (single bin over rain gage location for gage) and radar comparison. Figure 7.11 shows an example AMBER display. As implemented for flash flood monitoring, the interface provides access to the various levels of basin scale. It can be difficult to monitor 5,000–10,000 small basins so only those basins which exceed rainfall and rainfall thresholds can be displayed. Also, a database on results for all basins can be sorted and the ABR, FFG, Alert Status, and Basin Rate of Accumulation (BRA) output for each basin for each Alert Time Period.

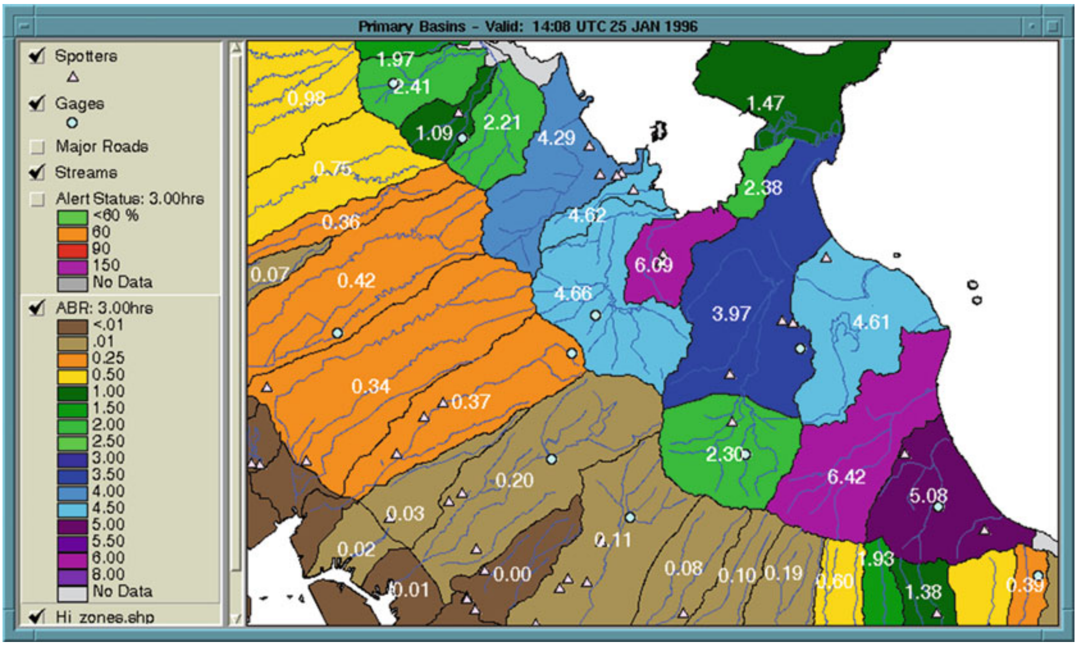

Fig. 7.11. Sample ArcView® GIS AMBER basin display. Basins are color coded by the 3-h ABR value for the basin. Streams and gage and spotter locations also are displayed. Numbers are the actual ABR in inches for the basin.

4. GIS FOR FLOODPLAIN MANAGEMENT

4.1. Floodplain Mapping Requirements

Extensions of surface water hydrologic modeling apply to floodplain mapping and GIS tools play an important role in accomplishing these activities. Given the regulatory authority of the Federal Emergency Management Agency (FEMA), it is their standards that establish primary mapping requirements for floodplains [22]. FEMA defines technical requirements, product specifications for Flood Hazard Maps and related National Flood Insurance Program (NFIP) products, and associated coordination and documentation activities.

Data required for floodplain mapping and management purposes are comprised of three general categories: (1) floodplain and watershed topography data to support hydrologic and hydraulic modeling, (2) physical data on built facilities for drainage control and buildings, and (3) administrative data on jurisdiction boundaries. These data are developed from a variety of sources using various GIS procedures and technologies and are ultimately collected into a comprehensive dataset supportive to project needs and longer-term multiple purpose management purposes. GIS tools for floodplain map updates have become standard practice. Floodplain maps and information prepared using traditional methods during the 1970s and 1980s are the basis for most current regulatory programs. Programs for map modernization are progressing, and GIS standards are promulgated for these.

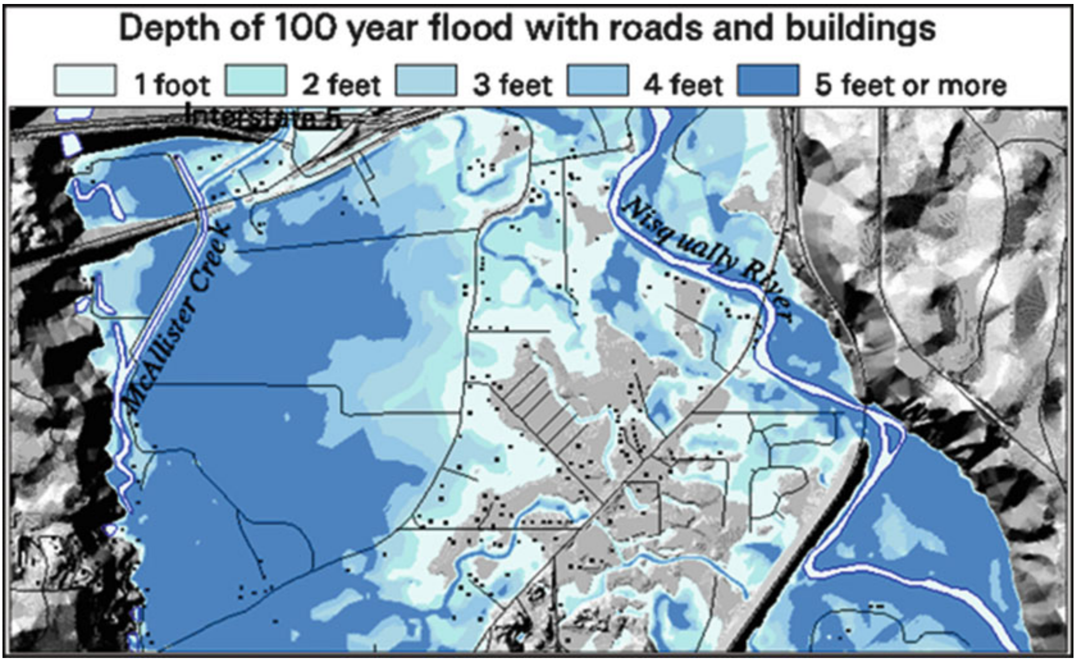

Fig. 7.12. Flood depth map with locations of roads and buildings [23].

A study by the USGS for the Nisqually River near Puget Sound, Washington [23], demonstrated the effectiveness of modern elevation data and GIS for updating flood maps. Existing floodplain maps were shown to have a number of shortcomings as follows: (1) based on out-of-date flood probability estimates, (2) hand drawn and difficult to manage, (3) have limited vertical accuracy, and (4) are expensive and time consuming to update. The GIS approach was shown to be (1) relatively inexpensive (10–20 % of traditional methods), (2) equally accurate and more detailed, (3) provided depth-of-flood details, (4) able to identify areas of uncertainty, and (5) digital, so analyses could be extended to other themes (e.g., roads and buildings) in support of risk assessments. GIS was used to create and manipulate digital elevation models representing the land surface and the flood surface. Determining the inundated area is a simple calculation: the flood surface elevation model is subtracted from the land surface elevation model at each location, resulting in negative values wherever the flood elevation is greater than the land elevation. A by-product of this calculation is flood depth which is important for damage and insurance assessments when intersected with building floor elevations (Fig. 7.12).

4.2. Floodplain Geodatabase

Given the extensive and disparate data sources required for floodplain mapping, there is a strong motivation to integrate the data into a comprehensive geodatabase. Doing so would provide advantages that a geodatabase provides in terms of standardization, removal of redundancy, concurrency control, and transferability, to name a few. FEMA has developed various data collection and reporting standards for floodplain studies as part of their nationwide program of map modernization. The two principle documents relevant to the design of a geodatabase for FEMA flood hazard mapping are (1) Appendix L of the Guidelines and Specifications for Flood Hazard Mapping Partners: Guidance for Preparing Draft Digital Data and DFIRM Database [24] and (2) Appendix N of the Guidelines and Specifications for Flood Hazard Mapping Partners: Data Capture Standards (DCS) [22]. These standards specify the current GIS databases used for archiving flood hazard models and results. Figure 7.13 presents the DCS relationship diagram for hydraulics.

4.3. Floodplain Hydraulic Modeling with GIS

The technical core of floodplain studies is the hydrologic and hydraulic modeling activities that lead to delineation of the floodplain boundary. GIS has become central to the conduct of such modeling studies, providing the means for integration of the various data involved, coordinating the various models, and providing high-resolution maps required for supporting flood management strategies.

There are a number of floodplain hydrologic and hydraulic (H&H) modeling packages that have been developed by the public and private sectors. H&H software varies in their capabilities for representing floodplain hydraulics and the level of GIS integration. In the 1-D approach, water flow is assumed to occur in one dominant spatial dimension aligned with the center line of the main river channel. The geometry of the problem is represented in the model by channel and floodplain cross sections perpendicular to the channel centerline. Two-dimensional approaches solve for water level and depth-averaged velocities in two spatial dimensions using finite difference, finite element, or finite volume computational grid approaches [25]. The 2-D models are appropriate for situations where there is opportunity for flood waters to spill out primary channels and flow overland, such as alluvial fans.

A popular public domain floodplain software package is the HEC-RAS, HEC-GeoRAS software package developed by the US Army Corps of Engineers. HEC-GeoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcGIS® using a graphical user interface (GUI) [19]. Figure 7.14 illustrates the type of display obtainable from HEC's GeoRAS [26].

An example of 2-D hydraulic modeling was demonstrated for the South Boulder Creek floodplain study. The MIKE FLOOD® model used in the study combines the traditional channelized one-dimensional (or 1-D) flow analysis model with a more physically based two-dimensional (or 2-D) model that analyzes distributed flow patterns away from the channel and across the floodplain. Due to the complexity of flow paths, the city updated the older 2-ft mapping with detailed 1-ft contour interval maps. These topographic data were developed using LIDAR technology which provided a DEM having 1-m grid spacing and a

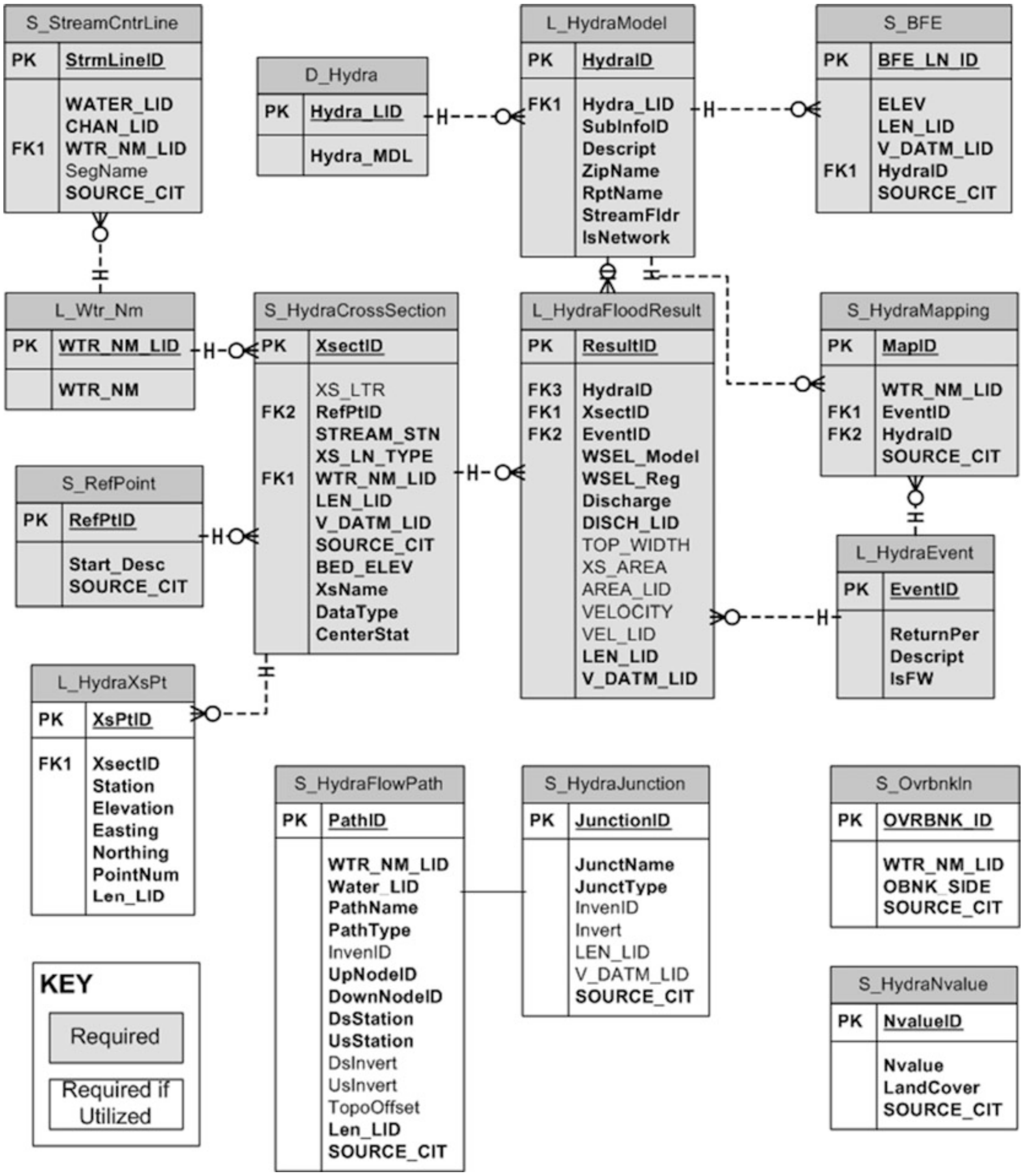

Fig. 7.13. Data Capture Standards relationship diagram for hydraulics [22].

vertical resolution of 15 cm. This allowed representation of the ground and structures in greater detail. Figure 7.15a shows the definition of one-dimensional channel and canal segments on a high-resolution digital orthophoto. Figure 7.15b shows a segment of the LIDAR DEM used as the land base for the two-dimensional model.

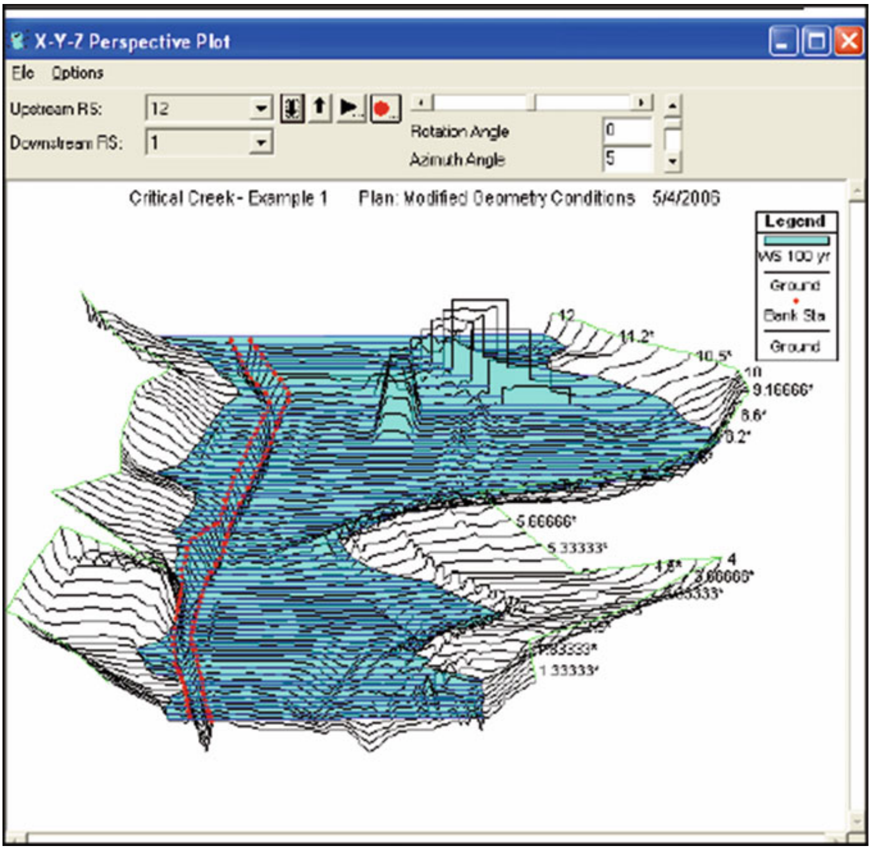

Fig. 7.14. HEC-GeoRAS perspective plot of river reach with a bridge [19].

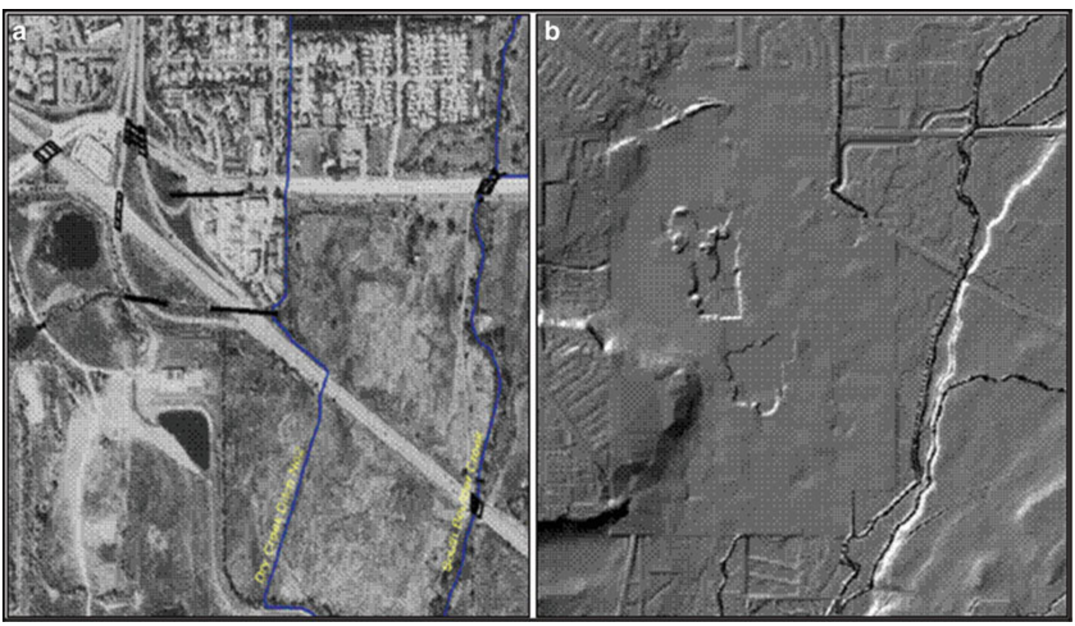

Fig. 7.15. Channel and floodplain hydraulic features were defined by (**a**) digital orthophotos and (**b**) LIDAR DEM for South Boulder Creek floodplain study. Courtesy of City of Boulder, CO.

5. GIS FOR WATER SUPPLY SYSTEMS

5.1. Overview

Water supply systems are fundamental infrastructure components sustaining community public health and economic productivity. This paper reviews water supply distribution systems and components, aspects of their design and operation, and GIS concepts and tools which support these activities. GIS tools are applied for demand estimations, network design, and system operations. GIS spatial data management and analysis tools enable these functions. Without GIS, required system parameters are often generalized. Spatial details on pipe connections are often reduced to a single value expressing average tendency over a group of connections which may introduce significant error. A GIS provides functions for development and preparation of accurate spatial information for input to network design simulation models and operations control.

5.2. GIS-Based Water Supply Demand Forecasting

Procedures for generating water demands for pipe network modeling using GIS were described by Wu et al. [27] and Prins and Bodeaux [28]. In general, water demands are based on land use maps augmented by a relational database, or geodatabase, which incorporates attribute data such as customer ID, land use category, water use records, and per unit planning factors. Customer billing records can be used to determine water demands given historic records. Geocoding, a standard GIS process to establish the location of customers based on their address, can be used to assign customer demands to a model using (a) nearest node, (b) nearest pipe, or (c) meter aggregation [27]. Figure 7.16 illustrates an example of nodal demand assignments by land use.

5.3. Pipe Network Design with GIS

Water supply distribution system design is accomplished using pipe network hydraulic models to simulate performance of the network under various design scenarios, typically for forecast maximum hour and maximum day plus fire flow demands. The pipe network design process is iterative in character involving specification of a pipe network layout having pipes of certain types and sizes. For reliability, it is desirable that the network be a looped system so that water can be delivered to all services even if a certain pipe is shut off for repairs. Topography can be a primary determinant of system layout to take advantage of gravity distribution that is more reliable and cheaper than pumping. Distribution storage tanks may be placed at strategic locations in the system to provide storage to meet fluctuations in use, provide water for fire-fighting use, and stabilize pressures in the distribution system. Also, pumps may be required to move water to high storage areas. It is necessary to calibrate the hydraulic model to ensure an accurate representation of the actual distribution system hydraulics.

Pipe network models are based on hydraulic flow and network theory and use the principles of conservation of mass and energy to represent flows and friction losses throughout a network. Pipe networks create relatively complex problems, particularly if the network

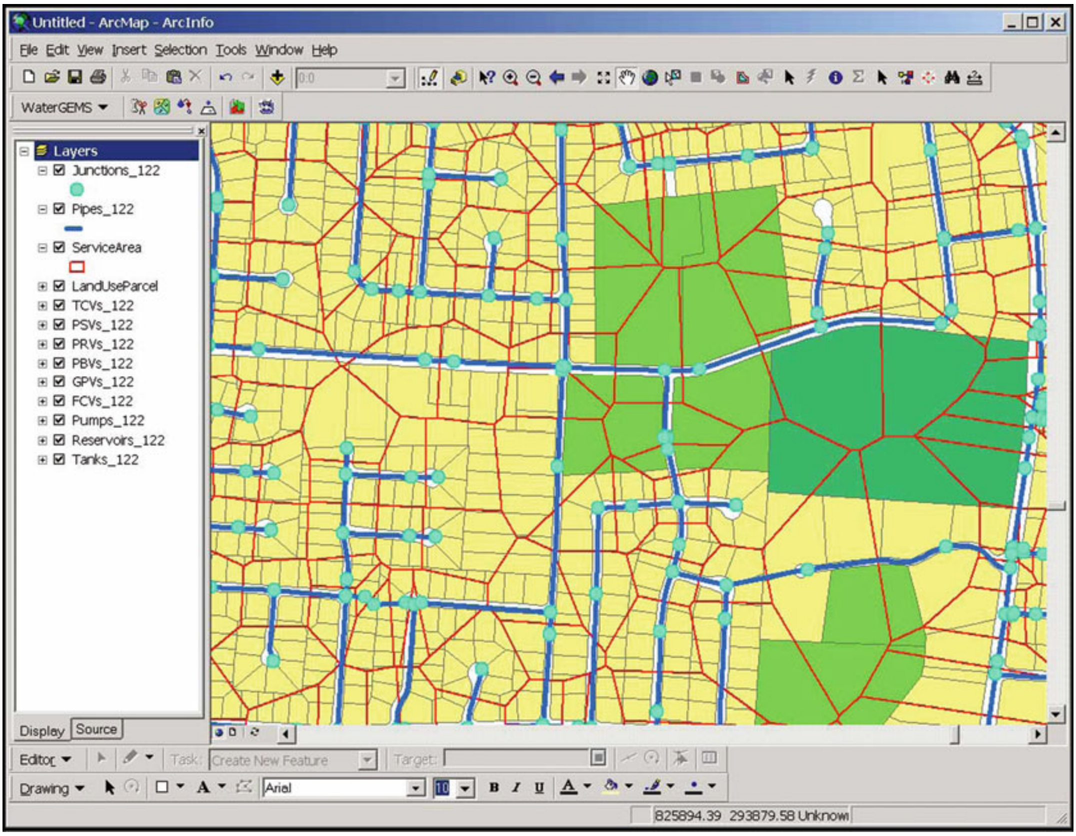

Fig. 7.16. Example of nodal demand assignments by land use [27].

consists of a large number of pipes, and solutions of these problems require sophisticated computerized mathematical procedures. Jeppson [29] and Walski [30] provide reviews of numerical solution procedures.

There are a number of modeling packages for simulating pipe networks that are integrated with GIS. The most common is the public domain EPANET model [31]. Other commercial pipe network software includes WaterCad® and InfoWater/H2Onet®.

GIS provides functions for development and preparation of accurate spatial information for input into the network design modeling process, which include network layout, connectivity, pipe characteristics, pressure gradients, demand patterns, cost analysis, network routing and allocation, and effective color graphic display of results. The GIS accomplishes database management operations for both spatial and attribute data, user-friendly dialog interfaces for data manipulation and output display, and models subsystem including both simulation and optimization.

An application of EPANET and InfoWater® GIS pipe network modeling capabilities was conducted by Szana [32]. The process used to create an all-pipes hydraulic model from GIS

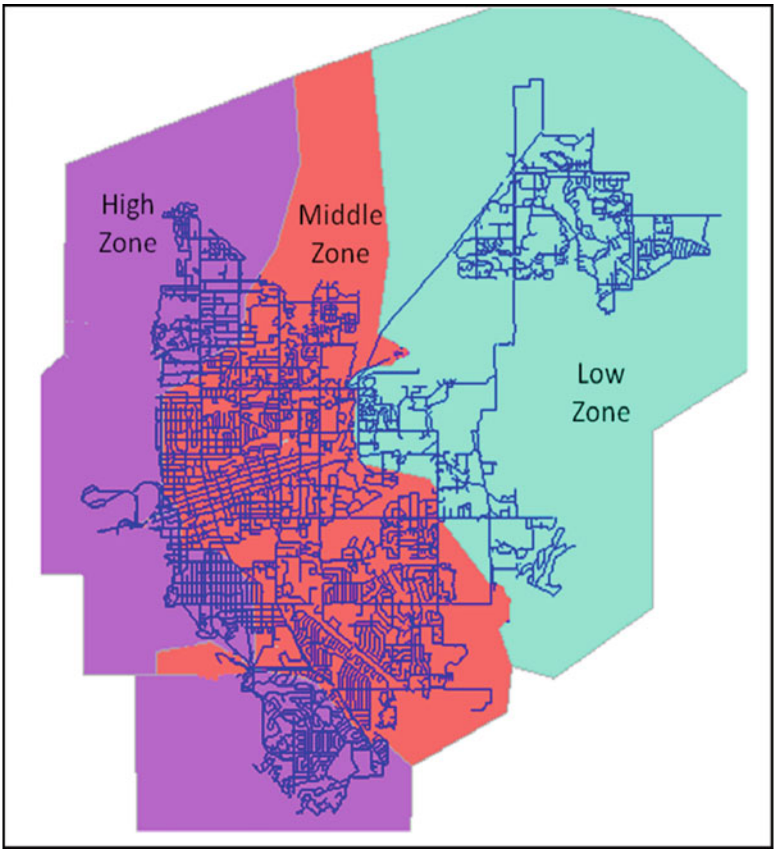

Fig. 7.17. Pipe network model completed with assignments to pressure zones [32].

data included (a) processing of initial GIS datasets, (b) importing data into the GIS, (c) formulating the initial hydraulic model based on the GIS pipe data, (d) error-checking for network connectivity, (e) assignment of node elevations based on the digital elevation model (DEM), (f) assignment of node demands (current and future), (g) calibration of the model for current conditions, and (h) simulations of alternative scenarios.

Processing of initial GIS datasets involved importing the ArcInfo® data from the city GIS department. The all-pipes model was created from the GIS pipes dataset which contained fields for all information useful to perform hydraulic and system analysis. A digital elevation model was imported and geo-registered to the other spatial datasets; elevation is a fundamental attribute of the hydraulic model, and all nodes, reservoirs, pumps, and tanks must have assigned elevations. A parcels dataset was imported to support land use demand factors and customer notification for maintenance and emergency conditions. Other GIS data were added, including the street network, parks, and other land features; these were for general map identification purposes and were not used for the hydraulic analyses. The final pipe network was completed and available for nodal demand assignments and simulations (Fig. 7.17).

Water use data from the billing system was used to represent the minimum and maximum demands. Demands were allocated to the model using a meter-closest pipe method. Demands for future growth or rezoning were estimated from the zoning designations where the system will serve in the future.

Model calibration was accomplished by adjusting parameters until model outputs matched field data collected with the utility's Supervisory Control and Data Acquisition (SCADA) system. This procedure involved two main processes. First, model parameters and attributes that can be physically tested and/or measured are adjusted to attain model results that more closely match actual results in the field. Secondly, pipe roughness, which changes over time and is very difficult to measure, can be optimized to minimize the difference between the model and field results. The initial model calibration was accomplished by trial and error, running model simulations and then viewing pressures, flow rates, tank levels, and water age. The process is aided by the GIS-based visual displays of pressures, velocities, and differences between monitored and simulated values.

6. GIS FOR GROUNDWATER HYDROLOGY

6.1. Overview

GIS has found extensive application for groundwater assessments as there are many types and large amounts of data involved. Proper evaluation of groundwater resources requires thorough hydrologic, geologic, and hydraulic investigations. The spatial scope may be quite local for a specific pumping well or range in size from a few hundred hectares to entire basins and even countries. Use of simulation and management models is widespread in such studies, and GIS has become a primary technology for coordinating the data management and providing the interface for groundwater model development.

6.2. GIS for Groundwater Modeling

Groundwater modeling tools are used to represent an approximation of the field data and to assess the behavior of the groundwater system under varying climatic conditions (drought conditions) or changes in water consumption, population growth, or changes in land use. The most popular computer model of the numerical type is the modular finite-difference groundwater flow model (MODFLOW) developed by the US Geological Survey [33]. MODFLOW simulates groundwater flow in aquifer systems using the finite-difference method. A variety of features and processes such as rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation also can be simulated (Fig. 7.18a). In this method, an aquifer system is divided into rectangular blocks by a grid (Fig. 7.18b). The grid of blocks is organized by rows, columns, and layers, and each block is commonly called a "cell." For each cell within the volume of the aquifer system, the user must specify aquifer properties. Also, the user specifies information relating to wells, rivers, and other inflow and outflow features for cells corresponding to the location of the features.

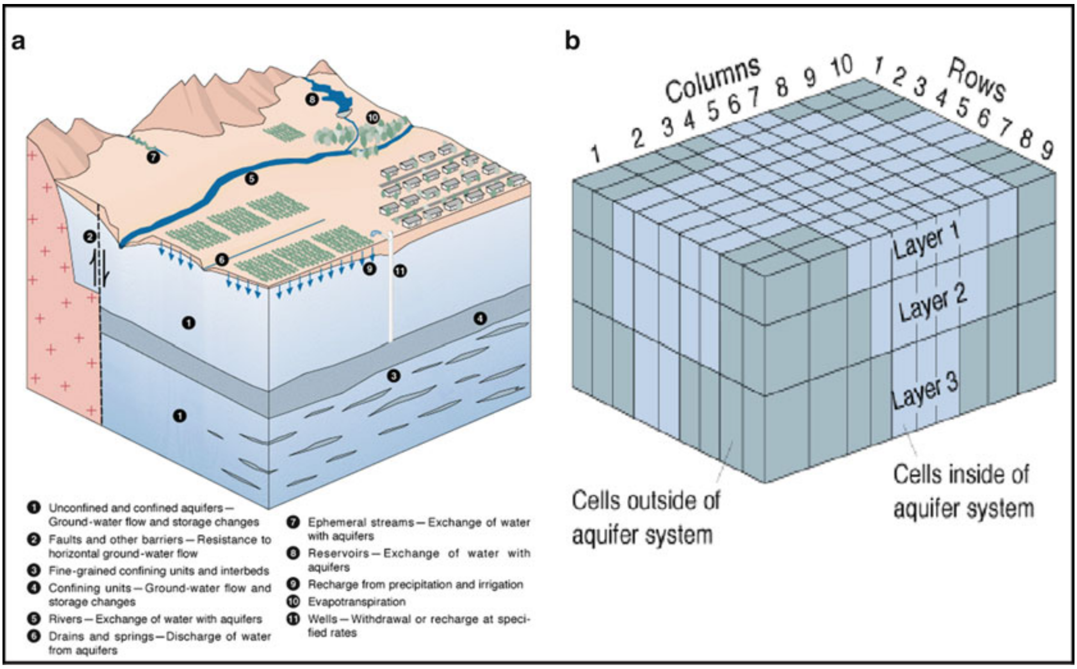

Fig. 7.18. (**a**) Features of an aquifer that can be simulated by MODFLOW. (**b**) The features are represented in a three-dimensional finite-difference grid [33].

Groundwater models require a number of disparate and large datasets which are difficult to manage. GIS can help with the modeling process by coordinating data collection, providing comprehensive database operations, supporting systematic model parameter assignments, conducting spatial analysis (e.g., spatial statistics) functions, and displaying model results in understandable color map formats. Groundwater systems are often represented using gridded data; grids are used to efficiently create and visualize spatial distributions for pre- and post-processing of the model [34]. Grid functions make it easy to compare and modify input data. Identifying attribute values of concern in large data files is made easier with GIS when they can be visualized in map formats. Most data is gathered at points, which are then interpolated using geo-statistical techniques into surfaces of elevations (land surface, piezometric). GIS grids, coverages, and shapefiles are used to create the majority of the input datasets for MODFLOW, including hydrogeology and stratigraphy, hydrogeologic parameters, boundary conditions, and initial conditions. Coverages and shapefiles are used to represent rivers, drains, and wells. Geoprocessing is used to create polygons with unique soils, precipitation, evapotranspiration, and land use, which can then combined to generate recharge and evapotranspiration arrays.

In concert with the surface water domain, there has been a movement toward a geodatabase approach for groundwater data and modeling support. Zeiler [35] described the ESRI geodatabase data model as an object-oriented model introduced with the ArcGIS® software.

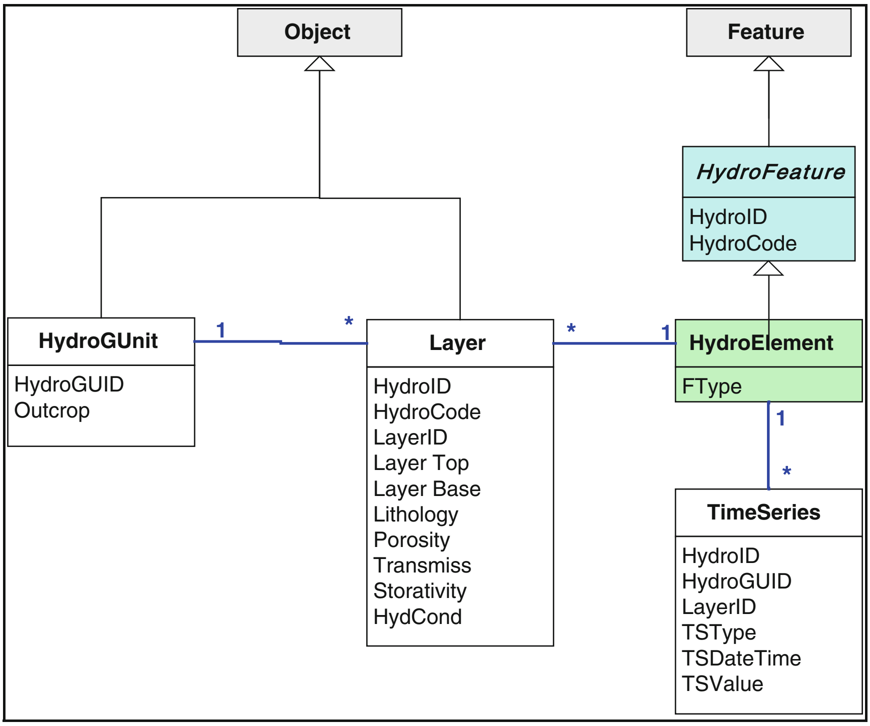

Fig. 7.19. Classes and relationship of the three-dimensional data model [36].

The basic form of the model contains a geodatabase, feature datasets, feature classes, and object classes. An example of a feature dataset would be a group of monitoring stations, where a feature class would be the observation well locations and the object class the water level data collected at all the stations. The model is packaged in a geodatabase, which contains the feature datasets. Feature datasets in turn contain all the feature classes in a model and the relationships among them within a common coordinate system. An object class is a nonspatial entity like a data table, and feature classes are objects plus spatial coordinates. Maidment et al. [36] extended the ArcHydro geodatabase concepts to include groundwater. Groundwater applications range from regional studies, which usually describe the flow in aquifers as two-dimensional, to site investigations that model the three-dimensional nature of the flow through the aquifer architecture. Figure 7.19 illustrates the classes and relationships of the three-dimensional data model.

6.3. Case Example: MODFLOW for Rio Grande Valley

The Rio Grande basin within Colorado is located in south-central Colorado and encompasses approximately 7,500 square miles. The primary feature of the basin is an open, almost treeless, relatively flat valley floor (known as the San Luis Valley) surrounded by mountains. Agricultural activities account for more than 85 % of basin water consumption with an estimated 638,000 acres under irrigation. The primary crops are potatoes, carrots, small grains, and alfalfa.

The basin has been the focus of a major groundwater modeling effort directed to assessing the amount of recoverable water [37]. The Rio Grande Decision Support System [38] program has been developed to provide the tools and information appropriate for water management of the region. The RGDSS was directed to addressing these groundwater issues by activities for groundwater modeling, consumptive use modeling, new data collection, and DSS integration. The groundwater simulation modeling effort required new data on streamflows, piezometric pressures, consumptive uses, stratigraphy, topography, and wells. GIS databases and tools of various types provided a primary means for accomplishing the project. The coverages developed for the RGDSS groundwater model included rivers/streams, canals, drains, surface irrigated lands, groundwater irrigated lands, wells, nonirrigated lands, soils, rim inflows, diversion locations, and gage locations. All GIS coverages were developed on a common datum and consistent units.

The groundwater computer modeling package MODFLOW was used as the primary simulation tool to analyze the movement and impact of pumping wells on the surface water system in the Rio Grande basin. Procedures for developing input files for MODFLOW were described by Rindahl and Bennett [39]. The groundwater modeling interface system (GMS) involved integration of GIS coverages, relational databases, and consumptive use model results into a coordinated package for generating input files required by the following MODFLOW packages: (1) basic package (2) block-centered flow package, (3) general head boundary package, (4) stream or river package, (5) output control, (6) solver package, and (7) drain package. GMS also exports the model cell grid system so that it can be processed by the ArcView® data analysis.

Calibration of the Rio Grande basin groundwater model was performed for steady-state (1990–1998) and average monthly (1970–2002) study periods [38]. It was determined to be adequate when the difference between observed and simulated flow values and heads was minimized while maintaining aquifer parameters within a reasonable range. Calibration included evaluation of (1) groundwater budget, (2) change in storage, (3) streamflow, diversions and gain-loss, (4) observation wells, (5) total evapotranspiration, and (6) other non-numeric data (e.g., dry cells, flooded cells). Figure 7.20 presents a residuals plot that shows the difference between simulated head and observed head for the 903 wells where observed data was compared to simulated values; the map display is for layer 1 of the model (the top most layer of the four-layer model). The residual plots indicate the model reproduces observation wells fairly accurately with better results in the center of the valley than the boundaries.

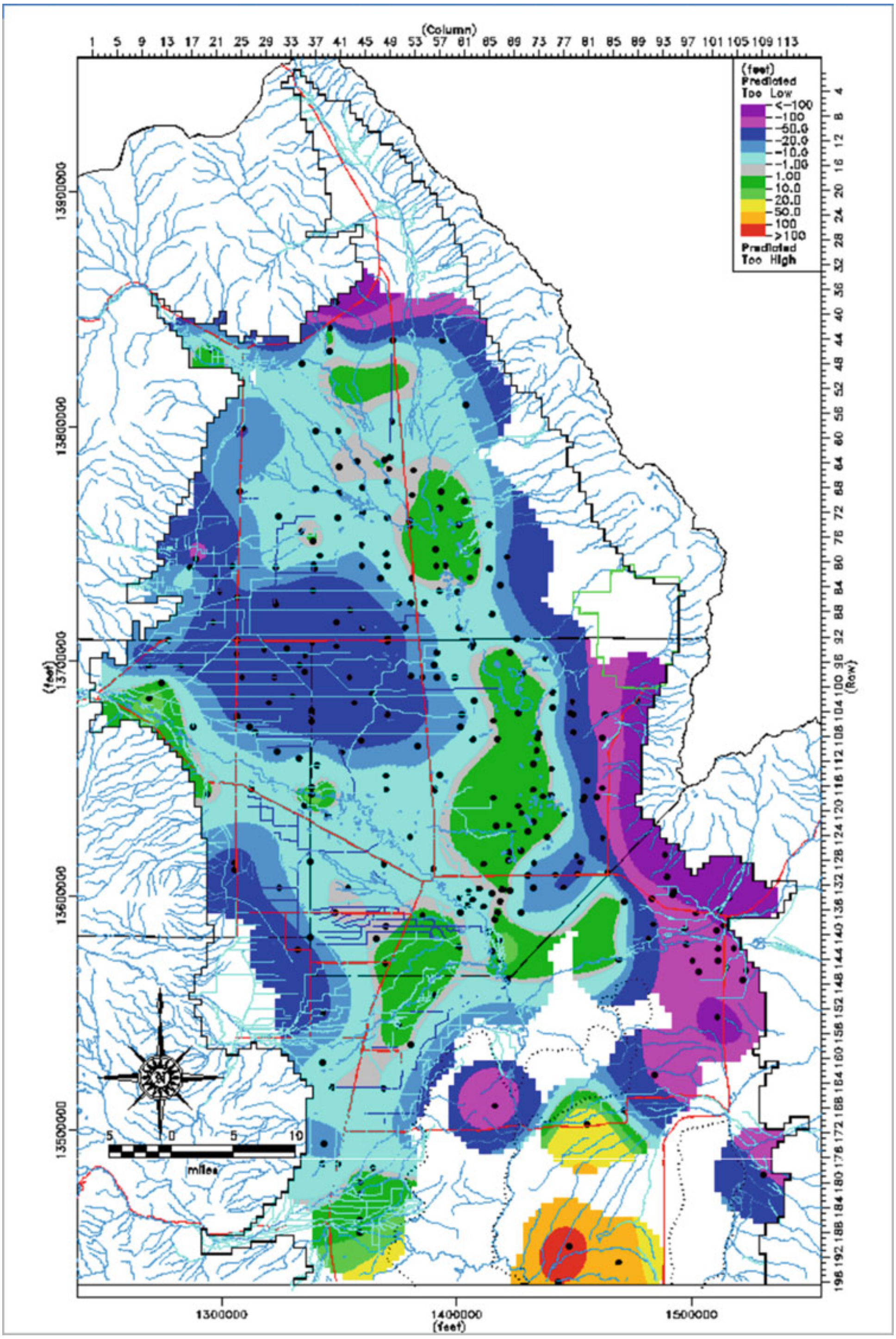

Fig. 7.20. Residual head for steady-state simulation for layer 1 of the Rio Grande groundwater model [38].

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