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Implementation of GIS for Water Resources Planning and Management

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Abstract: The geographic information systems (GIS) implementation process starts with the initial decision to use a GIS; proceeds through system selection, installation, and training; and up to data-base development and product generation. This paper discusses considerations related to each phase and focuses on other facets of GIS pertinent to water-resources planning and management. Many of these considerations involve critical choices that can pose significant challenges and impose substantial costs. An understanding of these challenges can expedite the GIS implementation process.

Introduction

Geographic information systems (GIS) is a rapidly evolving suite of technologies that consist of computer-based programs containing specialized algorithms and associated data-base-management structures, frequently in an integrated package. These systems are expressly designed to store information about the location, topology, and attributes of spatially referenced objects (such as rivers, wetlands, political boundaries, and roads). GIS can also provide analysis of the spatial properties (such as length, area, and perimeter) of these geographic objects. GIS can support many data-base queries tied to spatially referenced objects and their associated attributes. GIS systems also possess specialized spatial analysis functions, such as overlay of thematic layers and buffer-zone generation around objects. Also, most GIS systems provide for automated cartographic transformation and generation of graphic and cartographic products such as chloropleth and thematic maps. GIS systems provide other more-specialized spatial analysis functions: finding shortest paths in a network or calculating the areal extent of a watershed draining through a specified point given a digital elevation model (DEM).

Implementation related activities must precede full-scale project-oriented work. Phases of implementation identified in the literature (De Man 1988) include feasibility studies; selection of software, hardware, and peripherals; system installation; training; data conversion; data-base development; and finally preliminary product generation. A generalized flowchart of the GIS implementation process is presented in Fig. 1. We discuss each of these topics, along with other pertinent considerations such as accuracy of GIS

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J. Water Resour. Plann. Manage., 1993, 119(2): 184-205

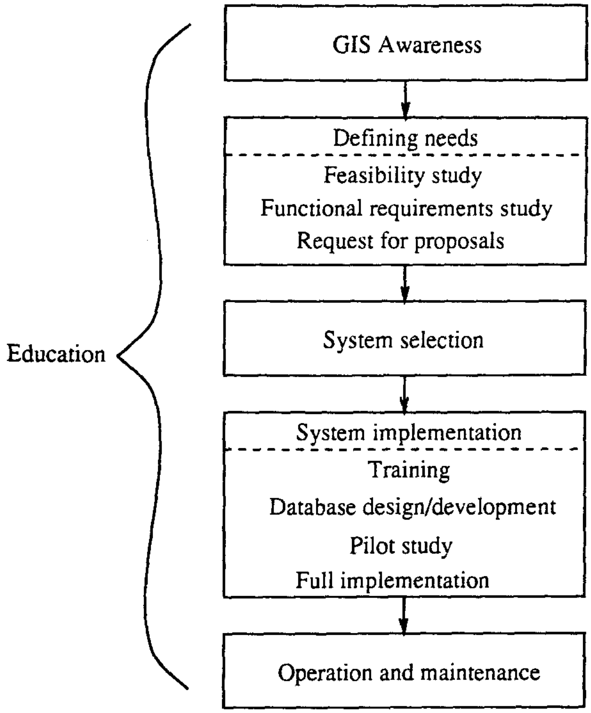

FIG. 1. Stages in the Implementation of GIS

data, structure of pilot studies, and the need for GIS users to develop practical and theoretical knowledge of this rapidly changing technology.

Becoming Familiar with GIS

The busy manager or professional may find it easy to treat GIS as a black box that transforms existing hard-copy maps and tabular data into digital products. However, a paramount task of any new or potential GIS user is the early investment of time and energy in order to gain a solid general understanding of the character, capabilities, and costs of GIS.

Typically, GIS users get much of their information on GIS from software vendors. Although vendors can be a very useful source of information on the capabilities of their specific products their sales representatives often are unable to educate potential users on general principles and concepts of GIS. They seldom provide a complete assessment of the users' needs or explain how GIS can contribute to meeting them. As a result, many users gain only a smattering of knowledge, through trial-and-error use of a GIS package, relying on the vendor-supplied manuals for guidance.

Reference Books

It behooves the user or potential user of GIS to take the initiative to learn more about this rapidly changing field. Numerous and proliferating sources of information exist about GIS. Books on the subject of GIS include *Principles of Geographical Information Systems for Land Resource Assess-*

ment (Burrough 1986), the original GIS primer; *Geographical Information Systems: Principles and Applications* (Maguire et al. 1991), an excellent and thorough two-volume set; *Geographic Information Systems: An Introduction* (Star and Estes 1990), which includes coverage of the relationship between GIS and remote sensing; *Introductory Readings in Geographic Information Systems* (1990), which has a wide range of reprinted articles about GIS; *GIS Applications in Natural Resources* (1991), which emphasizes forestry-related issues and; *Geographic Information Systems for Resource Management: A Compendium* (1989), which contains several articles on use of GIS in water-resources management.

Source Books

Source books of utility to the manager or researcher in search of knowledge about specific GIS solutions, systems and suppliers include *1991–1992 International GIS Sourcebook* (1991); *Intelligent Infrastructure Workbook: A Management Level Primer on GIS* (1990); and *Geographic Information 1991* (1991).

Journals and Trade Magazines

Several GIS journals and trade publications have appeared recently, including *The International Journal of Geographic Information Systems*, the primary scholarly journal in the field; *Cartography and Geographic Information Systems* (formerly, *American Cartographer*); *Photogrammetric Engineering and Remote Sensing*, which publishes a special annual issue on GIS; *GIS World*, the primary trade publication for GIS. Their annual survey of GIS software gives the best overview of software; and *Geo Info Systems*, a recent entry into the field, which is applications oriented.

Conferences

Annual conferences and expositions devoted to GIS and related subjects include GIS/LIS, hosted jointly by several professional societies; the Urban and Regional Information Systems Association (URISA) Conference; the American Congress on Surveying and Mapping and the American Society for Photogrammetry and Remote Sensing (ACSM/ASPRS) Conference; the EGIS (European GIS) Conference; the Association for Geographic Information (AGI) Conference; and numerous computer graphics and other specialty conferences.

Users Groups

Several users' groups for specific GIS systems hold annual meetings, including those of ARC-INFO, from Environmental Systems Research Institute (ESRI); MGE, from Intergraph Corporation; and GRASS. These meetings provide a forum for the discussion of specific GIS packages.

National Center for Geographic Information and Analysis

A valuable source of information on the latest research in GIS is the National Center for Geographic Information and Analysis (NCGIA). This National Science Foundation–funded research center is a three member consortium of the University of California at Santa Barbara (UCSB), the University of Maine, in Orono, Me., and the State University of New York, Buffalo, N.Y. The NCGIA sponsors research into key issues of GIS (such as accuracy of spatial data and spatial analysis), hosts conferences [such as the First Annual Conference on GIS and Environmental Modeling (Goodchild et al., in press, 1993)], and has fostered the development of a core curriculum in GIS (*NCGIA* 1990). This internationally recognized 1,000-page curriculum, along with 60 other technical reports, is available from the NCGIA office at UCSB.

Specific Water Resource GIS Information

Information about specific water-resource-related GIS requires more effort to obtain. Most published material about GIS applications to water-resources planning and management is contained in conference proceedings (Leipnik and Loaiciga 1991) or presented in special reports (Wright and Buehler 1989). The references cited in this paper provide an excellent starting point for a more in-depth exploration of this topic. Other sources include publications from the United States Environmental Protection Agency (Aller et al. 1987; *Geographic* 1989), United States Geologic Survey (*U.S. GeoData* 1991), and other agencies, as well as vendors, consultants, service bureaus, and universities, whose role is discussed later.

Defining Current and Future Role of GIS

Once the natural-resources manager intent on employing GIS has gained a modicum of familiarity with the technology, he or she must consider the appropriate role for GIS. Even those users who already have established systems should periodically examine their requirements for GIS and determine if their current system continues to meet those needs. Many current users keep obsolete hardware, software, or both, perhaps to justify a prior capital investment.

A GIS is often acquired as part of a specific project with a very limited time frame and goals. Although this mode of GIS acquisition and use may conform to fiscal realities, results are often disappointing in terms of database development and product generation. The user who acquires a system with only one project in mind rarely gets a good return on investment, simply because GIS is such a versatile tool if properly applied. The development of a GIS for a specific application can often support other analysis or management activities that utilize the same data base. For example, digital soil-survey data developed for agricultural applications can be used in water-quality studies, or vice versa (Howard and Barr 1991).

GIS often leads to changes in the way analysis and modeling of ground-water flow or rainfall-runoff relationships are performed (Harris et al., in press, 1993; Richards et al., in press, 1993). This technology encourages new forms of data input and display of results (Maidment, in press, 1993). Researchers are changing the fundamental structure of their models to take advantage of spatially distributed parametrizations, replacing the traditional lumped-parameter models (Fedra, in press, 1993). Therefore, the role of GIS should be defined both in terms of supplementing or replacing current organizational functions (such as manual cartography) and also in terms of future possibilities.

Feasibility Studies

Before committing resources to the acquisition or upgrade of a GIS, the prudent manager will perform a study of what the system will be used for and what resources are currently used to perform those functions. That study can be an informal internal discusion, or a full-scale cost-benefit analysis conducted by a highly specialized consulting firm. It is desirable, however, to have an objective party provide insights into this process.

Feasibility studies are difficult because many factors relevant to the analysis are uncertain. The state of the technology is constantly evolving in terms of functionality and costs; the new generation of workstations are orders of magnitude more powerful and significantly less expensive than their mainframe predecessors of past years, many of which are still running GIS packages. Regulatory demands facing resource managers, though often uncertain, are generally becoming more stringent. For example, the definition of what constitutes a wetland and what protections are required are in a state of flux. Finally, the availability of funding is tenuous and likely to be further constrained in the near future.

The decision not to adopt or upgrade a GIS, and to continue to rely on past practices, is deceptively easy to quantify in terms of costs and results. The costs of traditional methods of resource inventory, cartographic database access and query (searching through a filing cabinet or map file), and manual cartography are easily determined, though they are high in terms of skilled personnel time (Couch 1991). The results of traditional methods are also known; but when compared with the graphic impact, speed, and analysis capabilities afforded by a properly implemented GIS, the old methods are often judged inferior by a rapidly growing number of resource managers (Dickinson and Calkins 1988).

Functional Requirements Studies

A useful part of the GIS adoption decision process is a functional-requirements study (FRS). An FRS details the products to be produced by the GIS, the required data and the GIS functions that must be available. An FRS can be used to define the scope of the project and the basic structure of the implemented GIS. If the FRS is properly performed, it can become the primary planning document for the rest of the GIS implementation process and the basis of a request for proposals (RFP). The FRS phase has received considerable attention from GIS consultants. Highly structured methodologies for conducting the FRS have evolved, including the use of interviews, focus groups, and questionnaires.

Request for Proposals

Once a functional-requirements study or other feasibility study has been conducted, the GIS acquisition process can begin. The best way to handle GIS acquisition is to develop a request for proposals (RFP). An RFP should not be so narrow that it suggests only a single software solution; it should describe in detail the nature of the proposed data-base contents, the functions needed to create and manipulate the data base, and the products that are anticipated. Since a GIS represents a considerable investment of resources, a thorough study of available alternatives should be made before selecting any system. The RFP should be distributed to as many vendors as possible. Their replies should specify details of graphical representation (topological vector, raster, etc.), system functionalities, available interfaces to data sources, data-base-management systems, network and comunication protocols, and hardware compatibility. The results from a well-structured RFP should give management the information needed to make informed and defensible decisions.

Selecting Appropriate Software and Hardware

GIS Software

Today, the characteristics of the GIS are largely determined by software vendors. A sampling of popular GIS packages is presented in Appendix I.

J. Water Resour. Plann. Manage., 1993, 119(2): 184-205

Currently, private companies ranging in size from multinational corporations like IBM and Hitachi to single proprietorships dominate the GIS market.

University-developed software: Several GIS packages developed by universities primarily for educational purposes provide inexpensive alternatives. The raster-based GIS package IDRISI (Clark University, Worcester, Mass.) is perhaps the most popular example of this class of software. IDRISI is somewhat limited in functionality, yet it is an excellent educational tool and is continually being enhanced. Other examples include MacGIS (University of Oregon, Eugene), OSU-MAP (Ohio State University), and MAP II (University of Winnipeg, Canada).

Government-developed software: Government agencies are involved in GIS systems development. The U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) is notable for its Geographic Resource Analysis Support System (GRASS). GRASS is a raster-based product that has been widely applied to water-resources and environmental-impact-assessment applications. It is well supported and runs on many platforms. Several private vendors have developed sophisticated user interfaces for it. Linkages to various hydrologic models are being actively developed. GIS users likely to interact with the Corps could benefit from using GRASS.

Private-sector software: Cost of this software runs the gamut from several hundred dollars to several hundred thousand dollars. Scope ranges from large, fully integrated products offering most of the spatial analysis and representation possibilities available, to limited packages geared to specific applications such as automated mapping/facilities management (AM/FM), accessing and analyzing U.S. Census Bureau TIGER files, and analysis of remotely sensed imagery (*1991* 1991).

ESRI's ARC/INFO: The vector-based GIS package ARC/INFO [Environmental Systems Research Institute (ESRI), Redlands, Calif.] is very widely used. ARC/INFO helped to establish the market for GIS, and has more installations on more platforms serving more applications than any other available package (*1991* 1991). Mainframe, PC, and UNIX workstation versions of ARC/INFO are available, as are interfaces to many data sources, models, and data-base-management systems. The latest version of ARC/INFO addresses limitations of earlier versions with respect to the handling of attribute data and provides facilities for developing a graphical user interface. Independently developed software provides linkage capabilities between the INFO flat-file data-base-management system and relational data bases such as Oracle, INGRES, DB2, and Sybase. Limitations of vector-based systems such as handling of fuzzy data or use with applications such as fire-spread modeling are addressed by a new raster-based package from ESRI called GRID.

ARC/INFO is relatively complex, requiring a significant commitment of time and effort to use effectively. However, many successful applications of this system to natural-resources management demonstrate its utility to committed users. In the water-resources field ARC/INFO has been linked to such models as the Hydrologic Engineering Center's HEC 1 and HEC 2 models and other hydrologic models (Maidment, in press, 1993), to river basin models (Grayman et al. 1991), ground-water models such as MODFLOW (the U.S. Geological Survey's ground-water flow model), other subsurface flow and transport models (More et al., in press, 1993), and to finite-element contaminant transport models such as the coupled fluid energy solute-transport (CFEST) model developed by CH_2M Hill (Harris et al., in press, 1993).

Intergraph's MGE: Another highly functional GIS software package is Intergraph's Modular GIS Environment (MGE) software product, and related modules such as Modular GIS Analyst (MGA) (Intergraph Corporation, Huntsville, Ala.). As the names indicate, this software is organized into modules, so users need purchase only those modules relevant to their needs. MGE is a vector-based package with raster-supporting modules designed to operate in conjunction with Intergraph's Microstation 32 computer-aided design (CAD) package, and it offers the best available integration of CAD and GIS software. MGE has the ability to interface with numerous relational data bases, including ORACLE, INFORMIX, INGRES, and DB2. Specialized modules include three-dimensional computer-aided design (CAD), sewer management, contamination-site management, geophysical modeling, and other hydrologic applications. MGA is a module that supports spatial-analysis functions. These products were developed for the Intergraph UNIX-based workstation (a microcomputer version also exists).

Interfaces between MGE, and MODFLOW, AT123D (a contaminant-transport model developed by the Department of Energy), and statistical packages (such as 20/20) are included in MGE's environmental resource management and assessment (ERMA) system module. This module has been used to support hydrogeologic investigations at contamination sites including military facilities such as Vandenberg Air Force Base, Calif., and the Patuxent Naval Air Station, Md. MGE has also been used for water-resource-management activities by the Michigan Department of Natural Resources (Michael 1991).

Other GIS software: Other GIS packages used for water resources management include the following.

The INFOMAP system, from Synercom (Houston, Tex.), a vector-based package, has been used in a number of very-large-scale water-resource-related projects and linked by Woolpert Consultants (Dayton, Ohio) to the Storm Water Management Model (SWMM) (Cowden 1991).

The AGIS system, from Delta Data Systems (Picayune, Miss.), has been used to model flooding, using a variety of raster and vector input data.

SPANS, from TYDAC (Arlington, Va.), a raster- and vector-supporting package, is widely used in natural-resource-management applications, notably forestry.

MOSS, developed by the Bureau of Land Management and now available from Autometrica (Lakewood, Colo), is a vector-based package used in resource-management applications by government agencies.

GEO/SQL from Generation 5 Technologies (Denver, Colo.) is vector based, with limited spatial-analysis functions; it uses AUTOCAD as a front end and is linked to several structured query language (SQL) based relational data bases. GEO/SQL has been used to support ground-water contamination studies and in public water-supply-system-management applications.

The Earth Resource Data Analysis System (ERDAS, Inc., Atlanta, Ga.), developed for the display and analysis of remotely sensed imagery, is a useful component of a GIS relying heavily on remotely sensed data. ERDAS has been used in numerous environmental studies, including analysis of areas to be inundated by potential dam sites (Mitasova and Iverson 1991; Baffes et al. 1990).

Many other commercial GIS packages have been developed. The annual

J. Water Resour. Plann. Manage., 1993, 119(2): 184-205

GIS World software survey provides details on 150 different packages (*1991* 1991).

GIS versus Computer-Aided Design (CAD) and AM/FM

Some of the software products listed in the *GIS World* software survey are limited in terms of GIS functions such as spatial-analysis capabilities (for example, buffering and polygon overlay) and are more properly termed CAD packages. CAD output and GIS output may look similar, but the structure and function of CAD and GIS systems is very different. In the writers' opinion, users should avoid the temptation to use a CAD package and a separate data base as a proxy for a GIS. The nature of data storage in available CAD packages severely limits query of the data base, spatial analysis, and handling of cartographic transformations. Automated mapping/facilities management (AM/FM) software comes closer to GIS software in terms of its attribute data-handling capabilities, but generally lacks sophisticated spatial-analysis capabilities. However, for specific applications such as water-distribution-system mapping and maintenance, AM/FM software may be more appropriate than sophisticated GIS software, which offers the user functions that may not be needed or that may be overly complex for some users (Cowen 1990).

Spatial Decision-Support Systems

High-powered interactive systems running GIS and linked to hydrologic and other models and to decision-support tools such as expert systems, statistical packages, optimization programs, and enhanced graphics offer the natural resources manager a new paradigm for environmental analysis. This integrated approach is termed spatial decision-support systems (SDSS). This new technology is being used to support a wide variety of applications (Fedra, in press, 1993). The role of water-resource engineering in the evolution of SDSS will be highlighted in an Engineering Foundation conference on the application of spatial decision support systems to water resources management and planning that is scheduled for 1994, in Santa Barbara, Calif.

Computer Platforms

Personal microcomputers (PCs) versus mainframes: Just as with software, there are a number of choices available to the user for computer hardware. Personal micro-computers are easy to use and inexpensive. However, the large data sets with complex topology and numerous attribute relationships encountered in typical resource-management GIS applications imply that PCs may offer inadequate power. Until recently, serious GIS users were forced to run GIS programs and maintain their attribute data bases on mainframe computers, many of which had proprietary operating systems requiring GIS software specific to that machine. Mainframes have several disadvantages when it comes to GIS, notably complex operating systems, the need to support other tasks, and potential problems with end-user access to the system. However, some users may find the data-handling capabilities of mainframe (and mini) computers desirable and even essential for very large data sets.

Workstations: UNIX workstations appear to be the GIS workhorses of the 1990s. They offer an excellent compromise between the ease of access and simplicity afforded by a PC and the power of a mainframe. The rapidly increasing power and the relative affordability of workstations now provide the user access to powerful GIS coupled to large and complex data set and other decision-support tools such as hydrologic models, statistical packages, and optimization programs, on stand-alone or networked desktop platforms.

Peripherals

The optimal choice of peripherals will depend on the character of the inputs and outputs anticipated from the GIS.

Storage media: Typically include floppy disks, tape cartridges, reel-to-reel tapes, and various types of optical disks. Magnetic tape is an effective means of storing and transferring the large data sets encountered in GIS. However, data on magnetic tape must be read sequentially and the longevity of data stored on tape is limited. The character of tape media can be expected to change with the recent introduction of digital audio tape (DAT). Given the large size of the GIS datasets, compact disks (CDs) are particularly effective as a data storage and transfer media. Some GIS input data are already available in a CD read-only memory (ROM) format and more will be available soon (Lytle, in press, 1993). The erasable optical disk offers perhaps the best available medium form GIS data storage, access, and transfer, but this technology is still costly.

Digitizing versus Scanning

Data input and conversion devices include keyboards, scanners, and digitizer tablets. Digitizing involves a human operator who manipulates a line-following device (a puck or cursor) on a digitizer tablet, manually tracing line work from a map or engineering drawing and keying in the related attribute data simultaneously or subsequently. Scanning employs laser optics to automatically store the map or drawing as a digital image. The process involves less initial manual labor, although extensive computer and manual editing of the data may be required. Scanning is more rapid but more technologically intensive. The nature, quantity, and quality of the input data will help to determine which conversion approach is more appropriate. If scanning is deemed preferable, specialized service bureaus exist that can perform this activity, saving an end-user the substantial cost of acquiring drum scanners and related software (Armstrong 1991).

Output Devices

Some type of graphics-output device will be required by most users. An eight-pen color roll-type plotter or flatbed plotter is typical. If "fill" is desired on cartographic products, an electrostatic plotter may be more appropriate. Color thermowax printers and color inkjet printers offer another excellent output device for smaller-size graphics. Color output devices cost more than black-and-white and gray-scale devices, but they are well worth the investment if the output is going to be presented to outside parties or senior management.

Compatibility

Compatibility of hardware and software can be a serious problem with peripheral devices such as digitizer tablets or plotters. Generally speaking, a hardware-specific software driver is required to use any external input or output device. Some drivers for specialized equipment such as electrostatic plotters can be quite expensive; other peripherals simply may not be supported by a given software package. Before a GIS package or peripheral is acquired, intercompatibility should be confirmed.

System Installation

Once acquired, the GIS must be installed in its new operating environment. Getting a GIS system up and running can be a time-consuming task that requires input from highly trained consultants, or it can be as simple as putting a disk into drive A. In most water-resource-related applications, installation of the GIS software will probably require the assistance of several GIS experts, technicians, a data-base administrator, and technical assistance from the vendor.

Training and Human Resources Development

Since GIS is a relatively new technology, individuals with a strong background in its theoretical foundations and the necessary specific technical skills are rare. In many organizations, existing personnel—particularly cartographers and drafting personnel—will be retained (and ideally retrained) as "GIS specialists." Although this approach has many practical benefits, it can lead to serious problems. A significant difference now exists between the technical background necessary to master a PC-based CAD package (such as AUTOCAD) and the far more rigorous prerequisites of mastering a complex GIS.

Water-resource engineers and other in-house professionals can often become proficient GIS users who have the advantage of a thorough understanding of the sources and uses of the data and other GIS products. However, further specialized training may be needed in order to develop this expertise. Also, a change in attitudes about the ease and speed with which a GIS can be implemented may be in order. There are many tedious aspects associated with data-base development and product generation. Manual digitizing, is a very time-consuming task and requires great patience as well as some understanding of system commands. The entry of attribute data, which has lesser technical requirements, can be even more tedious. Map production requires considerable cartographic design background as well as patience with hardware quirks (Armstrong 1991).

Managers may also benefit from learning about GIS on a conceptual level. In this case, education rather than training (learning associated directly with operating the system), is more appropriate. In GIS education, considerations such as the sources and quality of spatial data, spatial analytical concepts, and the multitude of problems to which GIS can be applied should be stressed.

To develop GIS expertise, some form of structured training is generally needed. Software vendors generally offer well-designed training courses that teach the specific commands needed in their software package. However, vendors offer limited education in the general aspects of GIS and little or no coursework in water-resource-related aspects of GIS. The cost of vendor-sponsored training programs often inhibits learning about GIS fundamentals.

Educational courses in GIS are offered by universities and colleges (often through geography departments). However, these regular courses of study, though less expensive per hour than many vendor training programs, may take unacceptable amounts of personnel time. Moreover, regular GIS curricula seldom provide specialized study in water-resource applications of GIS. University- and consultant-sponsored GIS workshops offer a good alternative. A week of intensive and targeted study of GIS can make the investment in GIS software and supporting hardware worthwhile. The common complaint that the vendor training swamps underprepared participants can be mitigated by prior exposure to GIS fundamentals and relational-data-base and operating system concepts. Also, a GIS workshop can be structured to meet the specific needs of a user.

In large organizations, responsibility for the GIS may be assigned to the existing computer-systems data-base-management group. This approach usually assures that the technical aspects of the operating system, the character of the attribute data, and other functional parameters of the system are well comprehended. However, GIS is not yet a normal part of information-science curricula. Therefore, the nature of spatial data, the special characteristics of spatial-analysis algorithms, and the character of cartographic products may initially elude these traditional custodians. Furthermore, if the GIS is entirely in the hands of a computer-systems group, it may not be disseminated into the organization, leading to underuse.

An interdisciplinary approach is perhaps a more desirable (albeit difficult) solution, because of the diverse talents needed to utilize a GIS optimally. GIS should function as an integrating technology, allowing individuals and departments that previously worked autonomously to interact in new ways. An interdepartmental team composed of professional engineers, systems analysts, cartographers, data-entry operators, and others is probably best able to meet the challenges posed by GIS implementation and development. The more that team members are aware of concepts from other disciplines, the more satisfactory the outcome is likely to be.

An important practical consideration is that any employee who develops specialized expertise in GIS becomes a valuable commodity in the labor market. Therefore, some adjustment of status and/or job title within the organization may be warranted in order to retain individuals with GIS expertise.

Pilot Studies

Once a system has been acquired, installed, and tested and trained personnel are available to operate it, the data-base-development and product-generation process begins. Rather than launch into development of a GIS covering all aspects of the resource-management problem under consideration, it is advisable to select a representative geographically circumscribed "slice" of the overall area or problem for use in a pilot project. Pilot studies must have realistic and specific goals and timetables and should be designed to rapidly generate modest, yet representative, products, such as site-specific maps or sample data-base schema. Such products can be a tangible demonstration of GIS capabilities and will help to encourage a further investment in longer-term GIS development. A pilot project will also allow system administrators to gauge more accurately the costs of data-base development.

Data Sources, Accuracy and Data-Base Development

Sources of digital data: The most time-consuming part of the GIS implementation process is data-base development. Many organizations turn this function over to specialized service bureaus or other consultants, with obvious benefits. Fortunately, an increasing quantity of input data is now available in digital form. For example the Census Bureau's TIGER files provide street-map data and census-tract boundaries for the United States, the U.S. Geological Survey (USGS) has digitized most of its 1:100,000 topographic map sheets (and many 1:24,000 quad sheets), and private parties offer many types of digital cartographic data as well (*1991* 1991). The Defense Mapping Agency offers the 1:1 million digital chart of the world, and the Soil Conservation Service is converting its soil survey maps to digital form (Lytle, in press, 1993). Many of these products will be available in CD ROM format. Also, the U.S. Environmental Protection Agency (EPA) and other federal agencies make available much digital data in tabular form, such as water-quality data, that may be usefully incorporated into a GIS. Statewide GIS data bases on water resources are being developed in many states, including Minnesota, Massachusetts, Connecticut, Rhode Island, Texas, California, and New Jersey. Various local agencies in most states have developed GIS data bases, many of which are being shared among multiple users (Marshall et al. 1990). Unfortunately, the contents, formats, standards, and coverage of these data sets are often not uniform, and finding the specific source of digital data for a given area and theme can be difficult. The federal government has recently adopted the Spatial Data Transfer Format (SDTF) as a Federal Information Processing Standard (FIPS) to standardize formats for all federal spatial data. Also, the newly established nationwide network of 75 earth science information centers should provide a one-stop source for U.S. government spatial data (Kemp, in press, 1993).

Spatial data accuracy: This is an important and very active area of research in GIS. The accuracy and precision of different sets of digital data vary considerably. The integration of data with diverse formats and scales requires conversion prior to use. The conversion process introduces biases and errors that may be hard to quantify and rectify. Many functions within a GIS can produce results that are spurious, given imprecise input data. For example, a polygon overlay operation frequently produces numerous tiny, "sliver" polygons. These problems are of more than academic interest, because data in a GIS may be used in certain engineering or other applications in which accuracy is critical; also, data in a GIS may become the subject of litigation (Epstein and Roitman 1990). Therefore, it is important for GIS users to keep track of the history and character of data sources and manipulations. Provision for the retention of this "metadata" recording the "lineage" of the digital data should be built into the evolving data-base schema. For a more-detailed discussion of spatial-data accuracy see Goodchild and Gopal (1989).

Data-base design: The data base should be a key product and center of attention during the GIS development effort. Colorful graphics and hard-copy products such as maps may have a powerful visual impact and utility, but the real value of the GIS is determined by the underlying data and analytical functions, which allow that data to be used to make decisions. Besides the spatial data, data bases should contain attribute information for spatial objects, data on cartographic characteristics such as scale, projection and symbology, and appropriate links between tables and/or objects within the data base. Data-base development ideally should involve the creation of several views that support the special needs of different users. These views can be supported by careful structuring of the evolving data-base schema. Data-base design can be facilitated by techniques such as the entity-relationship approach (Teorey 1990).

Distributed data bases: As the size and complexity of a data base increases or when multiple users at dispersed locations wish to share some or all of the data in a GIS system, the physical location of and ease of user access to a system become considerations. With the advent of local- and wide-area networks, distributed data-base-management system (DDBMS) have become practical. In one DDBMS scenario, a central data base would be maintained on a mainframe at a headquarters location, while regional offices would extract and manipulate the portion of the data base relevant to their needs. Field offices would employ PCs to run less-powerful GIS software, which would access an even more limited data base. Localized changes in attribute or location data could be updated at the field-office level and sent by network up the organizational and data-structure hierarchy. Analytical results and more regional data input (remotely sensed data, for instance) could be divided into relevant geographic "views" at the central office and sent back to regional and field offices. Such rapid updating of data-base contents via the network creates a highly interactive environment [see Reed (1991) for a discussion of a forestry application].

Product Generation Issues

The central role of the data base as a GIS product has been stressed. Of course traditional products (and some unconventional ones) can also be generated by the GIS. Maps, engineering drawings, color slides, and overheads are the most familiar graphical products produced using a GIS. Reports based on the attribute data are another important product. Fortunately, these reports need not be reams of incomprehensible alphanumeric output. Interfaces between GIS packages and spreadsheets and statistical packages allow the user to generate histograms, graphs, charts, and tables from data contained in the GIS. As with all graphical products, the emphasis should be on impact and comprehensibility.

Role of Academics, Vendors, Consultants, and Service Bureaus

Since the whole GIS field is in a rapid state of flux, the roles of the varied GIS players are evolving, and frequently overlap. Convoluted yet fruitful collaborations of people from organizations of very different types are occurring. In addition to the organization adopting GIS technology, there are four other distinct categories of players in the GIS game: academics, vendors, consultants, and service bureaus.

Academics

Academics primarily contribute through their work in research and teaching. Research includes work on GIS data structures, development of new and expanded applications of GIS and integrated spatial decision-support systems, and three-dimensional representation and dynamic modeling capabilities within GIS (Hazelton et al. 1990). In addition, academics do some project-related work for government agencies.

Vendors

GIS software vendors do the largest portion of systems-development work. Vendors provide varying levels of support to users, depending on the company, the complexity of the product, and the willingness of the user to pay. In some cases, software may be so complex that use of a vendor-supplied consultant is a prerequisite for its installation. Some value-added retailers develop specialized accoutrements to existing packages. These might include a customized graphical user interface or a data interface to an existing modeling package or data base.

Consultants

Consultants can offer important assistance at several points in the GIS implementation process. They provide invaluable advice on system selection and customized training. Consultants help develop specialized interfaces between GIS systems, models, and/or data sources. Consultants provide one of the most cost-effective ways of obtaining GIS expertise, if it is only needed at a few critical junctures during implementation. GIS consultants run the gamut from one-man operations to multinational engineering firms (such as EBASCO or CH_2M Hill). Selection of the right consultant is a delicate decision and, in fact, a few consultants exist whose stock-in-trade is advising users on which GIS consultants they should retain.

Service Bureaus

Service bureaus primarily specialize in the often onerous task of assembling, converting, and creating GIS data bases. These firms have access to costly equipment such as large drum scanners, banks of digitizer tablets, and data-input terminals, all staffed by skilled operators. Acquiring such facilities is not cost-effective for most users. There are, however, several potential drawbacks involved in use of service bureaus. First, their services are expensive, especially for small projects. Second, the quality and content of material going into the data base is not under the direct purview of the ultimate users. Since the service bureau may not be familiar with the characteristics of the location from which the data are being acquired, obvious errors may go undetected until the data are deeply imbedded in the GIS and have been used to generate a product. Correction of such inadvertent errors will, of course, add additional delays and costs. To minimize these types of errors, close contact between the end-user and the service bureau should be maintained.

Special Issues Pertinent to Water Resources Management

Water-resources management has proved a fertile field for GIS technology. Linkage of GIS to computer models is particularly prevalent for surface and subsurface hydrologic applications. Nevertheless, GIS use in water-resource management currently lags behind that in forestry, urban and regional planning, resource inventory and assessment, land and cadastral information, and AM/FM in terms of numbers of users and applications. However, these other applications also involve water resources. Given the critical role of the hydrosphere in the human and natural environment in areas of abundance (and more so in areas of scarcity), management of water is central to the management of environmental problems. In turn, representation and analysis of water-related phenomena by GIS facilitates their management. Thus, it seems likely that GIS use will continue to proliferate in this area.

Raster versus Vector Considerations

Unique aspects of water and water-related problems suggest a special approach for their handling in a GIS. Most GIS are either raster- or vector-based systems. Systems claiming both capabilities generally convert data from the secondary form to the primary form prior to analysis. Often this produces a consequent loss of accuracy, precision, or both. As a rule, raster-based packages are more appropriate for management, inventory, analysis, and representation of resources that are distributed continuously across the landscape, such as forests and soils. Raster-based packages are also appropriate when the primary input data come in a raster format (such as remotely sensed imagery). Vector-based systems are more appropriate in applications in which the locations of objects such as roads, sewers, or political boundaries are defined precisely. Vector-based packages are also appropriate when vector inputs such as CAD data or drafted engineering drawings are employed.

Water-resource-related data can have high precision (e.g. sewer locations) or they can be fuzzy (e.g. wetland perimeters). Even objects such as rivers that are precisely represented on maps are often in reality highly variable. This suggests that the high precision afforded by vector-based GIS may be inappropriate. Conversely, raster representation can give objects a blocky appearance unsuitable for depiction of many features, particularly linear ones.

In any given water-resource-related project, all the foregoing considerations may appertain. For example, an aqueduct or pipeline project might best use a vector-based GIS for the hydraulic engineering and pipeline-corridor-construction phase, and a raster-based GIS for the environmental-impact-assessment study of the right-of-way area. Which type of package is most appropriate would depend on the specific application. Perhaps more than one GIS program would be optimal, although that implies learning more commands and/or additional acquisition costs and overcoming data-conversion and transfer problems.

Spatial Analysis Functions

Both raster- and vector-based GIS software have many spatial-analysis capabilities. Those most likely to be of interest to water-resource managers include area, length, and perimeter calculation; overlay of thematic layers; and buffer-zone generation. Buffer-zone generation is particularly suited to risk and/or impact assessment for objects or facilities with known locations. Several investigators have used a GIS to construct buffers around the locations of wellheads and the locations of known or potential contamination sites to facilitate risk assessments for wellhead-protection purposes. Overlay of thematic layers is useful for impact assessment or general site selection using spatial intersection of several different environmental themes (e.g. proximity to sensitive riparian habitat, slope, vegetation, soil type). Data layers maintained in the GIS, containing information on such regional acquifer parameters as depth to ground water, net recharge, aquifer characteristics, soil characteristics, topography, impact of the vadose zone, and hydraulic conductivity (the DRASTIC method variables) are used for aquifer-vulnerability assessment. Overlay of these layers coupled to buffer-zone generation around point sources of pollution is ideally suited to facilitating such aquifer-vulnerability assessments (Aller et al. 1987; Evans and Myers 1986).

Characteristics of Water Resources Data

Data used in water-resource management also have special characteristics. Most hydrographic data represent some nominal static average depth, shoreline perimeter, stream centerline, and so forth. Water bodies vary in their boundaries and properties: estuaries vary daily, rivers vary seasonally and in response to storm events, and large lakes may vary over decades. Temporal variability and indistinct boundaries are not well handled in current GIS systems. Dynamic phenomena may be represented by taking snapshots at several time intervals and running them sequentially to create a computerized movie, something that is only recently feasible. Recently it has been suggested that fuzzy data might be represented by showing regions with intermediate values in intermediate colors, for example if open water is shown in blue and dry land is shown in red, then wetlands might be represented in purple, with appropriate levels of color saturation and hue for areas of transition.

Representing Surfaces and Subsurface

Hydrologic and hydrogeologic applications of GIS often require representation of the earth's surface and subsurface. Rainfall/runoff-simulation applications require representation of the earth's surface. Various digital elevation models including those using grids, triangulated irregular networks (TIN), or contours are available for surface representation (Weibel and Heller 1991). Which model is appropriate depends largely on the nature of the terrain and the analysis performed. Rugged terrain may be more realistically repesented with a TIN, and, conversely, a grid model may be more appropriate to gentle terrain. Modeling of flow across a surface is more dynamically correct in contour-based models, easy but only approximate on grid-based models, and problematic on TIN-based models (Maidment, in press, 1993).

Hydrogeologists are concerned with the representation of the earth's subsurface, and hence with the need to represent cross sections, fence diagrams, stacked surfaces, and true three-dimensional volumes (*Three* 1989). The latter problem is beyond the capabilities of any existing commercial GIS package. Wire-frame models and other surface models as well as software capable of displaying geologic cross sections and borehole geophysical data (provided in products such as the PRE/MIER and EP/SECT modules from Intergraph and GEOBASE from Earthware) are the best proxy for true three-dimensional (3D) GIS currently available. However, "true" 3D software originally developed by firms such as Dynamic Graphics (Alameda, Calif.), primarily for the visual analysis of subsurface phenomena for exploration and production in the petroleum industry, is now increasingly being applied to environmental problems like the representation of subsurface contaminant plumes. These programs allow true three-dimensional volumes to be represented and manipulated, although the association of nongraphic attributes and access to spatial-analysis functions are limited (Webster-Scholten 1990).

Conclusion

Many challenges are associated with each distinct phase of GIS implementation. Considerations related to GIS implementation within a water resource management and planning context have been emphasized. Awareness of these considerations and the growing range of solutions now available will assist current and potential GIS users deal with the many difficult environmental, land- and facilities-management issues facing water-resource managers and planners.

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APPENDIX I. SOFTWARE

Comparison of GIS and related software; analysis functions are assessed in the following order: buffer, map algebra, surface, network, polygon, and image processing (T = has the function; F = does not have the function) (*1991* 1991).

Name: Atlas*GIS
Company: Strategic Mapping, Inc.
Cost: $1,000s
Operating systems: DOS
Platforms: PC
Structure: Nontopological vector
Analysis: T,T,F,F,T,F

Name: ARC/INFO
Company: Environmnental Systems Research Institute
Cost: $1,000–10,000s
Operating systems: UNIX, DOS
Platforms: PC, workstation, mini
Structure: Topological vector with raster
Analysis: T,T,T,T,T,T

Name: ERDAS
Company: ERDAS, Inc.
Cost: $1,000s
Operating system: UNIX, DOS, VMS
Platforms: PC, workstation, mini
Structure: Raster
Analysis: T,T,T,F,T,T

Name: GEO/SQL
Company: Generation 5 Technology, Ltd.
Cost: $10,000+
Operating system: UNIX, DOS
Platforms: PC, workstation
Structure: Topological vector
Analysis: T,T,T,T,F,F

Name: GRASS
Company: U.S. Army Corp of Engineers
Cost: free to $1000s
Operating system: UNIX
Platforms: PC, Mac, workstations, mini
Structure: Raster
Analysis: T,T,T,T,F,T

Name: IDRISI
Company: Clark University

Cost: $100s
Operating system: DOS
Platforms: PC
Structure: Raster
Analysis: T,T,T,F,T,T

Name: Interactive Surface Modeling
Company: Dynamic Graphics, Inc.
Cost: $10,000s
Operating system: UNIX, VMS
Platforms: workstation, mini
Structure: Nontopological vector
Analysis: F,T,T,F,F,F

Name: MAP II
Company: John Wiley and Sons
Cost: $10–100s
Operating system: Mac
Platforms: Mac
Structure: Raster
Analysis: T,T,T,T,T,T

Name: MapInfo
Company: MapInfo Corp.
Cost: $100–1,000s
Operating system: UNIX, DOS, Mac
Platforms: PC, Mac, workstation
Structure: Nontopological vector
Analysis: T,T,F,F,T,F

Name: Modular GIS Environment
Company: Intergraph, Inc.
Cost: $1000s
Operating system: UNIX, DOS
Platforms: PC, workstation
Structure: Topological vector with raster
Analysis: T,T,T,T,T,T

Name: SPANS
Company: TYDAC Technologies Corp.
Cost: $1000s
Operating system: UNIX, OS/2
Platforms: PC, workstation
Structure: Raster/Quadtree
Analysis: T,T,T,T,T,T

Name: System 9
Company: Computervision
Cost: $10,000s
Operating system: UNIX
Platforms: Workstation
Structure: Topological vector
Analysis: T,T,T,T,T,F

Name: GIS Plus
Company: Caliper Corp.

Cost: $1,000s
Operating system: DOS
Platforms: PC
Structure: Topological vector
Analysis: T,F,F,T,T,F

Name: MapGrafix
Company: ComGrafix, Inc.
Cost: $1,000s
Operating system: Mac
Platforms: Mac
Structure: Nontopological vector
Analysis: T,F,T,F,T,F

Name: MapBox
Company: Decision Images, Inc.
Cost: $100s
Operating system: UNIX, DOS
Platforms: PC, workstation
Structure: Raster
Analysis: T,T,T,T,F,F

Name: TerraSoft
Company: Digital Resource Systems, Ltd.
Cost: $10,000+
Operating system: UNIX, DOS
Platforms: PC, workstation
Structure: Raster
Analysis: T,T,T,F,T,F

Name: GENAMAP
Company: Genasys II, Inc.
Cost: na
Operating system: UNIX
Platforms: PC, workstation
Structure: Topological vector
Analysis: T,T,T,T,T,F

Name: GeoVision's GIS
Company: GeoVision Systems Inc.
Cost: na
Operating system: UNIX, VMS
Platforms: workstation, mini
Structure: Topological vector
Analysis: T,T,T,T,T,F

Name: Graphics Design System (GDS)
Company: McDonnell Douglas
Cost: $10,000+
Operating system: VMS
Platforms: workstation
Structure: Topological vector
Analysis: T,T,T,T,T,F

Name: MIPS
Company: MicroImages, Inc.

Cost: $1,000s
Operating system: DOS
Platforms: PC
Structure: Raster
Analysis: T,T,T,T,T,T

Name: PMAP
Company: Spatial Information Systems
Cost: $100s
Operating system: DOS
Platforms: PC
Structure: Raster
Analysis: T,T,T,T,T,F

Name: INFORMAP
Company: Synercom Technology, Inc.
Cost: na
Operating system: UNIX, VMS
Platforms: PC, Mac, workstation
Structure: Topological vector
Analysis: T,T,T,T,T,F

Name: MicroImage
Company: Terra-Mar Resource Information
Cost: $1,000s
Operating system: DOS
Platforms: PC
Structure: Raster
Analysis: T,T,T,F,T,T

Name: MacGIS
Company: University of Oregon
Cost: $100s
Operating system: Mac
Platforms: Mac
Structure: Raster
Analysis: T,T,T,T,F,F

Appendix II. References

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