CONSTRUCTING A GEOGRAPHIC INFORMATION SYSTEM FOR WATERSHED MANAGEMENT

by Peter G. Rowe and Bill A. Bavinger

INTRODUCTION

In recent years the rapid development of geographic information processing with computers has created applications that are in many senses often more difficult to understand than the problems to which they apply. In addition to being highly technical, geographic information systems tend to be tied to specific applications and specific types of data. Many researchers (Tomlinson, 1972; Dueker, 1974; and Calkins, 1977) agree that today's data processing capabilities often far outstrip our general understanding of the spatial aspects of many problem areas. We are at a point in the development of geographic information systems where we risk losing sight of our basic mission to understand more fully the spatial distribution of natural and man-made processes. Therefore it seems appropriate to survey the development of some geographic information system applications and their terminology. Following this brief survey, the general concept and specific components of a geographic information system, which forms a fundamental part of research and development at the Rice Architecture Computer Laboratory, will be described and illustrated.

TERMINOLOGY AND DEVELOPMENTS IN GEOGRAPHIC INFORMATION SYSTEMS

Maps are one of man's important inventions. Like written languages, they are a way of graphically expressing and communicating mental concepts and images. But whereas language communication has been studied in detail, map communication has not. In fact, as Kolacny (1969) points out, cartographic theory and practice have been concerned almost exclusively

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with the creation and production of maps rather than with the theory and practice of their use. Little is understood about the actual workings of the form of communication that a map offers (Robinson and Petchenik, 1976).

Both early and contemporary attempts to use mapped information are well documented by Steinitz et al. (1976). Maps are commonly used by planners in so-called overlay analysis. This technique requires that a list of environmental features of interest to the planner be prepared and that this list be arranged so that features are ranked in order of assumed decreasing (or increasing) sensitivity to land-development impacts. The occurrence of each feature within a study area is displayed on transparent maps as varying degrees of shading, from darkest in areas where the feature is most abundant to unshaded where it is absent. When these individual maps are placed one over the other, composite shading of certain areas becomes apparent. Shaded areas are given an environmental "suitability" interpretation according to the combined sensitivity of the individual features used to prepare the composite map. Map overlays have been widely used to identify and evaluate alternative development sites within a study area, beginning at least as far back as the work of Manning before World War I. Extensive use of this technique, also referred to as "sieve mapping," was made in Great Britain during the 1920s and 1930s (Abercrombie, 1922). In the U.S., applications of this approach were made to highway location in the 1960s (Lewis, 1962; Alexander and Manheim, 1962). The work of Ian McHarg in the late 1960s (McHarg, 1969), however, is probably the best known application of map overlay analysis. Attempts to computerize the approach are also fairly numerous (Ward and Grant, 1970; Krauskopf and Bunde, 1972; and Rowe and DeLeon, 1973), and several recent attempts to refine the basic technique are well summarized by Hopkins (1977).

The applicability and appropriateness of the computer for coding, storing, and managing map-related information is fairly obvious by now. Just as colors or gray-tone shades can be used to delineate geographic features, so can digital signals or their symbolic equivalents. For large amounts of geographic information, current computer storage and manipulation capabilities are often far more convenient than their "manual" counterparts.

Cooke (1971) describes the development in automated geographic information systems as evolving from a largely manual assignment of location codes and feature descriptions to fully automated storage, retrieval, processing, and display of geographic data. In this evolution he identifies at least three phases. The first phase, taking place roughly between 1961 and 1964, saw the development of the first geocoding systems, such as the Automatic Location Table (AULT) and the Street Address Conversion Systems (SACS). During the second phase, between 1964 and 1969, the first nationwide geocoding system (Address Coding Guides, or ACG) was developed. The familiar DIME system (Dual Independent Map Encoding), used by the

U.S. Bureau of the Census, came about during the third phase (1969-1971).

During the 1970s, and subsequent to Cooke's survey, the private and public development of automated geographic information systems has been intense. Tomlinson (1972) identified over 500 different individuals or groups working on geographic information systems. Today the number of major applications, or systems, is in the hundreds, and the number of people working in the field is in the thousands. In spite of this apparent diversity, if not complexity, several basic approaches for the successful development and application of geographic information systems can be discerned.

But first it is important to define some of the terminology. Several authors (Steinitz, 1970; Tomlinson, 1972; and LaCasse, 1974) have documented and defined many of the terms used in geoprocessing. In defining some of the more common terms, this paper borrows from these earlier contributions.

Geographical data are pieces of quantitative or qualitative information obtained by measuring the location and certain aspects of the land, the environment, and its resources and population. Often a distinction is made between "image data" and "attribute data." "Image data" describes the type and spatial disposition of the sampling points, whereas "attribute data" describes the characteristics of relevant features at each sample point (e.g., conditions of soils). The ratio of "image data" to "attribute data" is sometimes used to describe the general "shape" and efficiency of a data base (Calkins et al., 1977).

Geocoding, or geographic coding, is the act of specifying and encoding attribute data according to its geographic location. A *geocode* is the index by which the location of attribute data is recorded. It may be nominal (e.g., city names, street names), ordinal (e.g., postal zip codes, census zones), or cardinal (e.g., the latitude-longitude coordinate system or the Universal Transverse Mercator [UTM] System).

Several other terms often associated with geocoding are *nodes, segments,* and *areas* or zones. *Nodes* are point locations expressed by a pair of coordinates usually referenced to a cardinal index such as latitude-longitude. A *segment* is a line joining two nodes, and an *area* is a portion of a map bounded by a set of nodes and segments.

Within the geocoding process, and particularly with the use of cardinal indices, there are a number of ways in which spatial information can be encoded (see figure 1). The most widely used approaches include grid or cell systems, polygonal systems, topologic systems, and pixels with raster techniques. A *grid* or cell system is composed of a matrix of equal areas, usually rectangular, produced by applying a uniform system of straight lines over the map area in both the x and y direction. By contrast, a *polygonal* system attempts to preserve the locational integrity of map features by recording

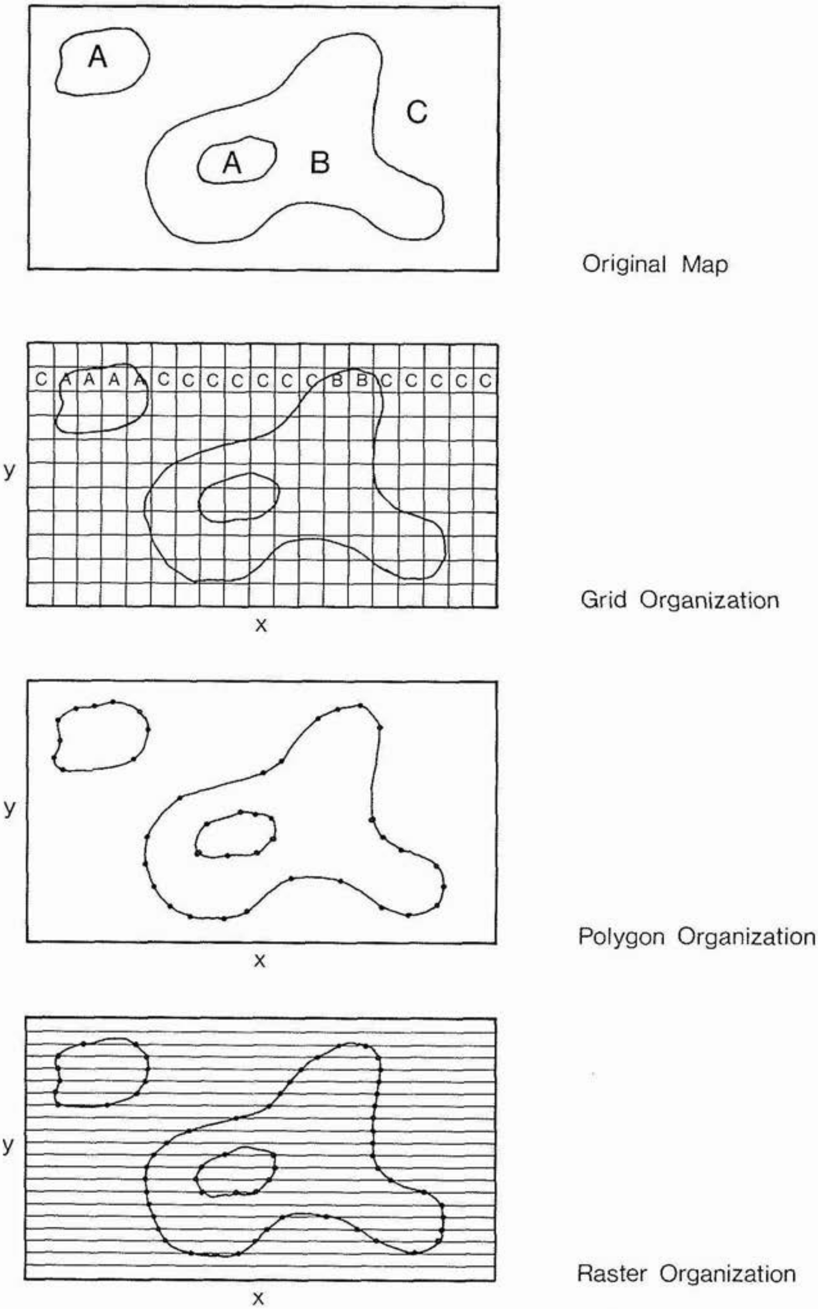

FIG. 1. ALTERNATIVE DATA REPRESENTATIONS

the *x-y* coordinates of all the significant inflections on a line delineating the boundary of the features. In effect, it produces areas bounded by three or more segments. A refinement of the polygonal system is the *topologic* or *chained-arc* approach, whereby lines and areas are represented as a network of nodes, or line endpoints, and boundaries (segments) connecting the nodes. A *pixel* is an individual picture element that in NASA remote-sensing parlance has come to represent a very small grid cell or single data point. In this technique the map area is essentially saturated with pixels. *Rasters* have been borrowed at least in terminology if not in actual practice from the composition of a television image, and involve a line-by-line horizontal scan of an image or matrix of data points.

One of the fundamental issues in the development of a geographic information system is the selection of an appropriate approach for recording "image data." The use of any of the data formats discussed in the preceding paragraph, as well as various types of input technology (manual coding, digitizing, and scanning), has its own particular problems. To find the right combination of data input technique and data format that will meet individual user needs, not to mention anticipated data volumes and types, is often a difficult task. For example a debate, with arguments of long standing, usually surrounds the decision to use a grid cell system or a polygonal system. Chrisman (1975) points out that although grid systems generally represent map feature boundaries less accurately than polygonal approaches, and although they essentially stemmed from programming expediency, their use is now reinforced by a supporting technology of satellites, raster scanners, and special purpose computers. Similar technological refinements have been made to the support systems and special requirements for maintaining polygonal systems, improving their efficiency and practicality. Both systems are widely used. Generally speaking, the polygonal form is adopted for information systems where the major concern is accurate cartographic retrieval and aerial measurement. The grid system is more widely used where locational accuracy is less important but where the ability to combine the attribute data from several non-contiguous features is a high priority. Although the debate continues among technicians as to the relative merits of one approach over the other, certainly no one system can be regarded as the preferred method in all situations. In fact, the debate itself is becoming less relevant with the emergence of information systems that incorporate both approaches and the capability of referencing data from one to the other (Dueker, 1975).

Two large government-sponsored geographic information systems, the Landsat System and the DIME System, require special mention. Landsat is the name given to a series of experimental satellites, and their associated terrestrial data processing units, that provide remote-sensored imagery of the earth's surface. Currently there are two satellites in circular near-polar orbits, providing data for a given location every eighteen days. Each satellite is equipped with television cameras and multispectral scanners, and the readings from these devices are digitally coded. The ground systems then analyze the digitally coded data and process them into spatial images. One of the major problems encountered in this process of alteration to visual form has been "recognizing" the images and classifying them into conventional schemes of land-use and land-cover. However, major strides have been made in overcoming this obstacle, as shown by recent developments of the ER-MAN System (IBM, 1976).

One of the most popular general purpose Geographic Base Files is the Census Bureau's DIME file. Before mid-1972, some 196 Standard Metropolitan Areas had DIME files prepared. The DIME System (Silver, 1977) views a map as a combination of linear graphs and alphanumeric data points. The linear graphs can be imbedded in a variety of planar surfaces, thus defining areas bounded by graph segments. Typically the areas and their associated alphanumeric names, or codes, define city blocks, the graph segments define streets, and the vertices define street nodes. The area codes are allocated to the linear segments that bound them, street names are allocated to specific line segments, and node numbers are allocated to vertices. All segments containing area codes must join up, and street name codes must be contiguous. With this coding scheme, the DIME system greatly facilitates the collation of separately established external indexes, such as city directories, within the DIME file itself. Though it is very useful in urban areas, the DIME system has limited usefulness in rural areas where the sparser rural road system leaves interstitial areas poorly differentiated and where rural postal addresses are often difficult to allocate to specific line (road) segments.

RAGIS: A USER-ORIENTED GEOGRAPHIC INFORMATION SYSTEM

The second part of this paper is devoted to describing our attempt to create a user-oriented geographic information system for planning purposes. Also described are several applications of this system to watershed management.

In a planning context, the major requirements of a geographic information system were postulated as follows:

1. ease of operation by non-programmers,
2. flexible data storage and retrieval,
3. the provision of support for analytical and modeling applications, and
4. the capacity for allowing exploration of the data for the purposes of defining inherent structures and relations.

To support these basic functions, a geographic information system called RAGIS (Rice Architecture Geographic Information System) was developed. Its basic structure is shown in figure 2. Largely because of limitations in available resources, not all elements of the system have been fully implemented. However, the existing system does provide at least a provisional definition of the overall design. Throughout the following discussion, care will be taken to distinguish those elements of RAGIS that are developed from those that are not.

The Command and Edit language

One of the central features of the information system is the use of a host language to support and control its operations. From the outset the major users of RAGIS were expected to be researchers and decision-makers who have no particular interest in becoming deeply involved in the basic development of computer hardware and software. Therefore, developmental work was directed towards allowing the user to work with the computer directly, stressing English syntax languages, conversational input-output modes, and on-line interaction. We felt that this approach would allow a non-programmer the freedom to store, manipulate, and retrieve data consistent with the problem at hand, rather than having to learn specialized computer languages and complex operation codes.

The computer language Speakeasy (Cohen and Pieper, 1977) was found to be most appropriate for RAGIS. Speakeasy is an extensible language that comes with broad general operating capabilities but that also allows users to include functions and operations peculiar to their classes of problems. These special functions or operations may in fact take the form of algorithms written and compiled in other system-supported languages, such as FORTRAN, and simply linked into Speakeasy's language processor. These linked load modules are called *linkules*. To the user, linkules are a vocabulary of English language key words that allow the associated programs to be called and executed by name. During the development of RAGIS, many linkules specifically related to mapping and spatial analysis were established. In fact, RAGIS has become a subsystem within Speakeasy consisting of some 250 programs and special operations for geographic information processing.

Speakeasy executes in the Time Sharing Option or in Batch mode and has an English-language-based syntax that incorporates the conventional mathematical notation for operators, operands, and resultants. A desk calculator mode is also available for use at any time, allowing special computations to be performed at a computer terminal.

Data encoding, storage, access, and display

At present the primary encoding device used within RAGIS is a CRT

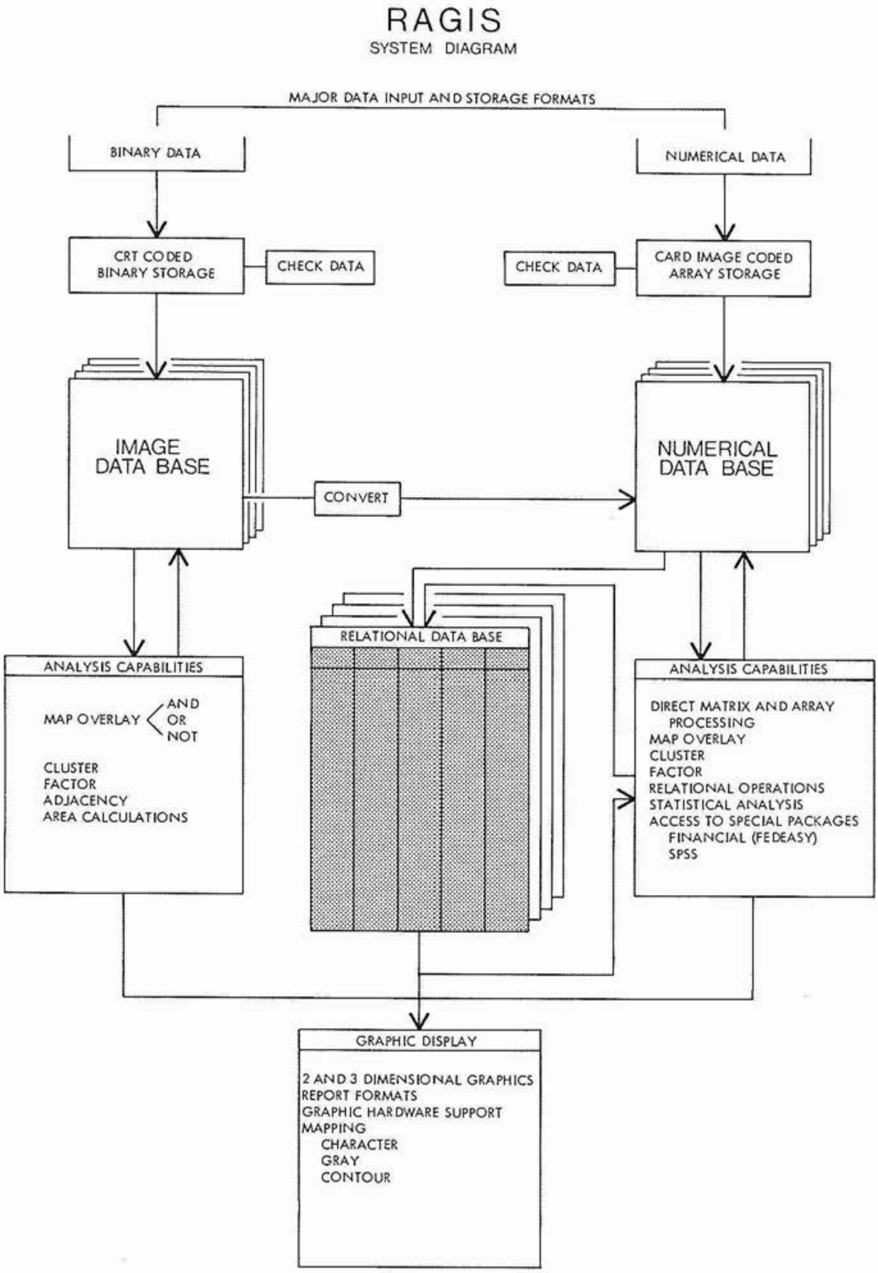

FIG. 2. RAGIS SYSTEM DIAGRAM

(cathode ray tube). A data-encoding linkule establishes a uniform grid of cells (64 × 48) as a two-dimensional array across the CRT screen. Maps or other spatial features to be coded are reproduced at the appropriate scale as black and white film positives. The film positive is then placed on the screen and the pattern of each feature visually coded in a raster-like fashion as a dot pattern. For the purposes of accurately representing features that are only partially present in particular grid cells, a separate dot pattern can be created for each appropriate interval of coverage. For example, a soil type may be coded with four distinct dot patterns representing 0-25% presence, 26-50% presence, 51-75% presence, and 76-100% presence. Checking the encoded data is accomplished on-line at the CRT screen simply by displaying each dot pattern and checking it against the film positive overlay. For contiguous areas of a homogeneous feature, the encoding process can be simplified by coding the extremities of the feature in each line of the raster scan and automatically setting the intermediate points to produce the appropriate dot pattern.

The coded data is stored in computer memory as a logical bit string, with each image forming a distinct binary pattern. This form of storage directly utilizes the computer's memory switches and results in considerable savings for basic storage, retrieval, and display operations. Each data pattern is assigned a unique alphanumeric code or name and to the user becomes like any other word in the system. Access is achieved by simply calling for the pattern by name and having it displayed or integrated into a computational sequence in the appropriate manner.

A wide variety of data display alternatives is available interactively within RAGIS. Data may be tabulated according to some predetermined format with considerable flexibility. Character maps and gray-tone maps can be produced either on-line or in batch mode. Because of hardware limitations, gray-tone maps involving character overstrikes can be achieved only in the batch mode. However, these can be scheduled from the terminal at a variety of scales. The line-drawing functions available to the CRT enable feature outlines to be represented and three-dimensional perspective and orthographic projections to be made of features' distributional characteristics. A variety of different types of *x-y* plots and curve-fitting options is also available.

Spatial analysis capabilities

In addition to providing access within the Speakeasy format to a variety of standard analytical packages, such as SPSS, several special-purpose routines have been developed within RAGIS. As described in the previous section, data primarily reside within the system in the form of a binary pattern. Conversion of this information into the numerical form that might be necessary to support some external modeling or analysis is accomplished by assigning appropriate values to specific binary patterns.

Map overlays, similar to applications mentioned earlier in the paper, can also be executed with RAGIS. In addition, the logical operators of "and," "or," and "not," or combinations of these operators, can also be applied directly to several data patterns for the purpose of searching for common or exclusive characteristics.

Several multi-variate statistical analysis techniques have been incorporated allowing the relational structure of attribute data and image data to be explored. The principal techniques involved are cluster analysis and factor analysis. The cluster analysis technique employs a centroid method (Bavinger, 1976) and can produce "maps" and tables of the results. The factor analysis technique also employs a fairly standard approach (Bavinger, 1976) and incorporates graphic output in the form of a three-dimensional spherical plot of the results.

Other operations routinely used in conjunction with geographic data bases, such as area calculations and contouring between points, have been incorporated as distinct functions within RAGIS. A variety of common array manipulations can also be performed in conjunction with the data base. In fact, as the need has arisen for particular operations to be performed on spatial data, new linkules have been incorporated within the system.

Data management

Recently a number of data-base management models have been developed to handle large volumes of data and have been applied within geographic information systems. As described by Date (1977), there are three general conceptual models for data-base management. They are the hierarchical model, the network model, and the relational model. In the hierarchical model, relations among data are represented in the form of "tree" structures where each item is linked in either a "superior" or "subordinate" position with respect to other items. The structure of relations in the network model usually takes the form of a directed graph without necessarily positioning the data items into a hierarchical format. Representation of relations in the relational model essentially takes the form of a tabular index with combinatorial operations based on a relational calculus (Codd, 1970).

A relational data management subsystem of Speakeasy, called Rspeak (Schlichting, 1977), was recently integrated within the RAGIS system for use with spatial data. This addition greatly facilitated data retrieval operations, particularly when the query involved finding combinations of "attribute data," and formulating the results of these combinations as further data items. Unlike application of the hierarchical model, the creation of relations among data that are inherently non-hierarchical was greatly simplified. Also the creation of complex "many-to-many" relations, which are often difficult to handle with a network model, could be readily accomplished. Although the development and application of the relational approach have not progressed to the point where its usefulness within RAGIS can be fully evaluated, the early results are quite promising.

RAGIS as a communications medium

As pointed out by Dueker (1976), among others, a geographic information system has many of the elements of a communications system. One of the principal ideas behind the development of RAGIS was to view a geographic information system more as a communications medium than as a fixed set of procedures for encoding, storing, manipulating, and displaying data. An attempt has been made to provide a variety of formats in which these types of procedure can be performed on an "as needed" basis.

In many ways the analogy to more traditional graphic media is even more direct. Within RAGIS the data are seen almost literally as a graphic image and the system software as the "artist paraphernalia" for re-representing the image. In a less metaphorical vein, we have attempted to integrate, under a single information processing system, a number of special purpose functions and operations that jointly allow acceptance, organization, and representation of data in a variety of forms.

Applications to watershed management

RAGIS has been used on several floodplain management projects primarily for the purposes of organizing the inventory and analysis of land use and environmental data, and in support of land-use and hydrologic modeling activities (figure 3). In fact, much of the developmental work within RAGIS has been accomplished in the context of watershed management applications.

The spatial data bases constructed for these projects usually conformed to a cardinal referencing system such as latitude-longitude or the Universal Transverse Mercator System. The data points themselves took the form of a uniform rectangular grid cell system with individual grid cells ranging from ¼ km × ¼ km (15.45 acres) on one project, to about a 70 acre grid cell on another project. The variation in grid cell size was primarily due to resource and data constraints rather than to any operating constraints of the system itself. All spatial information was coded in the manner described previously. The data base typically incorporated land-use and ground cover information classified according to the system of Anderson et al. (1972), soils information classified by hydrologic subgroup, and other environmental and economic data such as the location of natural hazard conditions and land value. To improve the spatial resolution of the data representation, the attribute categories were defined so as to allow the partial presence of a fea-

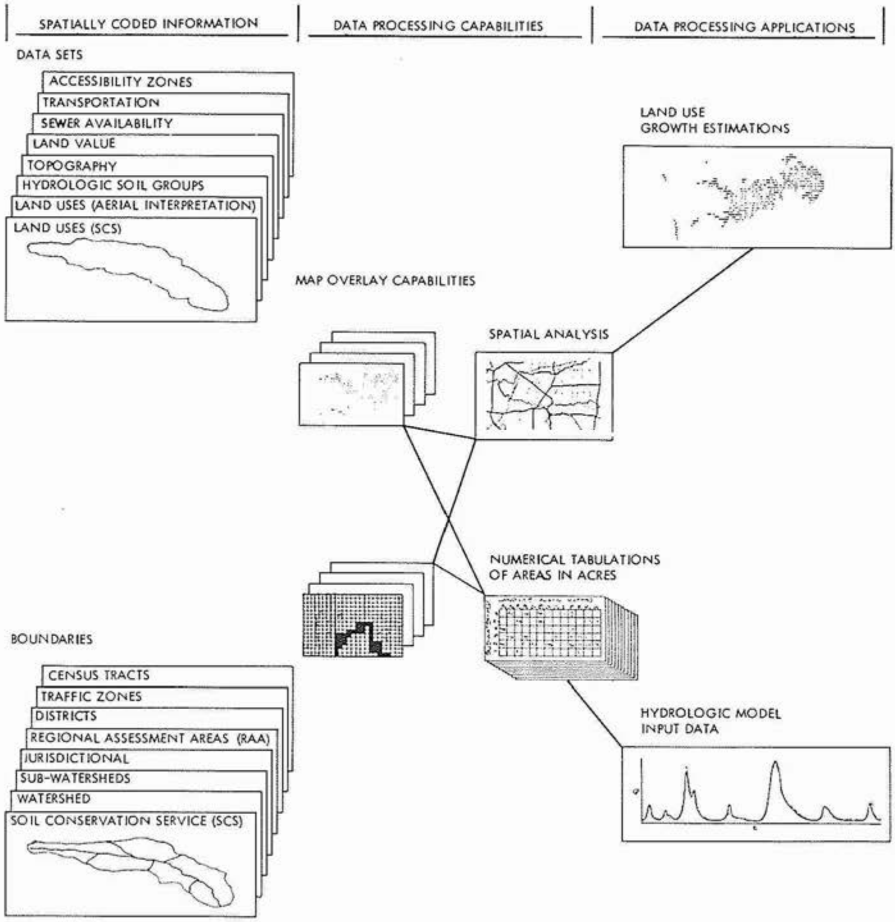

FIG. 3. APPLICATION OF RAGIS TO FLOODPLAIN MANAGEMENT

ture in a grid cell to be coded accurately.

A special form of the area calculation was developed to support the hydrologic modeling activities. Models such as HEC-1 and HLAND (Bedient et al., 1977) require data describing soil and cover conditions to be furnished by subwatershed area. By using the subwatershed delineations as a "mask" in conjunction with the logical map overlay operations, the number of cells, or partial cells, for each desired feature within a subwatershed could be "counted" and the appropriate areas computed. This operation greatly facilitated iterative application of the hydrologic models under varying cover and land-use conditions.

A basic step in the process of modeling future land-use distributions also required disaggregation, or re-aggregation, of data from one set of geographic units to another (Rowe et al., 1979). To perform these functions, extensive use was made of the RAGIS system in a manner similar to that described above. In addition, the land-use modeling activities required special arrangement of data to describe overall patterns of transportation accessibility, the ranked distribution of environmental constraints, and cost information such as land value. These requirements were met within RAGIS in a semi-automated fashion.

A particular application of RAGIS, requiring some further development, relates to the calculation of overall damages likely to be suffered in a flood with a particular frequency of occurrence. With accurate topographic and land-use data coded in the data base, the backwater elevations associated with a flood could be overlaid and related in turn to a set of damage functions, thereby permitting an estimate of the aggregate damage to be expected from the flood.

CONCLUSIONS AND FUTURE WORK

Developments in the area of data-base management in general, and geographic information processing in particular, continue to expand and diversify rapidly. Common agreement has generally been reached on the practicality if not necessity of using geographic information systems to supplement many planning activities. The ideal form of such an information system, should such a thing exist, however, is still very much open to debate. Technological developments are becoming more and more specialized, bringing with them a terminology that to many users is arcane. There is little doubt that many of the central problems of spatial representation have been solved, and a large number of systems is available for routine use.

The principal orientation of the development of RAGIS has been towards providing a system that is fundamentally easy to use by a non-programmer. To this end, the concept of an information system has been thought of as being a "medium" capable of "naturally" supporting a full range of data-processing functions. The system at present falls well short of this ideal, although we have simplified use to a certain extent, allowing flexible data processing without imposing the requirements of fixed procedural protocols. The use of the relational data model in conjunction with geographic information seems particularly promising and has the potential for greatly facilitating exploration and multiple use of geographic data.

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