APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS

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Contents

Summary

This article presents a discussion of applications of GIS at various levels leading to decision making toward sustainable socioeconomic development and conservation of natural resources. The discussions focus on various aspects of database preparation, storage and retrieval formats, and output displays using various software. Examples involving interdisciplinary studies and socioeconomic and environmental sciences in various geographic regions are presented to demonstrate potential applications of GIS. The final products of such applications include suitability maps for various land uses, resource availability, and vulnerability maps. These are accomplished using different software developed by different vendors, which integrate data that is then retrievable for informed decisions using analysis and modeling at various scales.

Various applications have different user requirements based on vendor specifications. Environmental planning and management requires the spatial data analyses and management capabilities of environmental decision support systems (EDSS), which integrate monitoring data and, through modeling, enhance solutions to particular problem areas including environmental impact assessments, which include soil erosion and pollution hazards and their underlying factors. Applications in hydrology and water resources couple GIS with specific models of spatial attributes such as land use and precipitation patterns, usually for response prediction of, say, floods and sediment yields. This information can be useful in the support of management and water resources operations including improved understanding of hydrological process dynamics. Other applications are the reduction of the risk of property damage in settlements, urban planning and modeling, and other socioeconomic applications. Here data layers are transformed by modeling land use dynamics to discover socioeconomic impacts.

Constraints and limitations of GIS applications include the generalization of data for heterogeneous areas due to insufficient scale resolution, data incoherence from merging data from different sources without due regard to reliability of each source, and lack of quality data at resolutions suitable for specific applications. The potential for more GIS applications also exists. This calls for more GIS software and hardware research and better models describing precise natural process dynamics. These models can then be associated with GIS to produce maps for interactive multimedia use at all scales, which will optimize decision making.

1. Introduction

1.1. Definition and Scope

A Geographic Information System (GIS) is a computer-based information system for input, management, analysis, and output of geographic data and information. It deals with collection, storage, retrieval, manipulation, analysis, and display of spatially related information. GIS systems are important tools for managing natural and other resources at all scales ranging from local to global. GIS capabilities include the overlay of information provided by different thematic maps according to user-specified logic as well as derivative map outputs.

Although GIS has been around since the 1960s, applications have expanded in the 1990s. Many software systems have now been developed to cover a wide range of fields such as earth and environmental sciences, natural resource management, terrain modeling, agriculture, forestry, construction engineering, land use policy and development control, population distribution, settlement, transport, education, and health planning. The expanded use of GIS in many areas of resource development has also necessitated the need for modern systems that incorporate analytical models with integrated powerful query languages to provide solutions to many spatial problems. Due to the multiplicity and diversity of applications, task-specific systems have been developed. They include systems for engineering, property-based information, generalized thematic, statistical and land-parcel mapping, environmental planning systems, and image processing systems associated with Landsat and other remotely sensed data.

1.2. Concept

GIS stands for Geographic Information System. Geographic refers to earth science, which studies regions, resources, people, etc. Earth has a spatial component. The land extends in all directions, within which all things or attributes exist. Anything happening or existing in space is spatial or spatially distributed. It must have a geographic reference that is, be geo-referenced. Also, there must be definable boundaries or limits in space. Information is simply any facts or data about a given space on Earth. Examples include slope, rainfall amounts, population, road networks, and vegetation. These may collectively be referred to as attributes, factors, or variables within a defined space on Earth, e.g., the location, country, drainage basin, etc. Systems are a structured set of objects or parts that are related to one another or which operate together as one whole unit following a defined pattern.

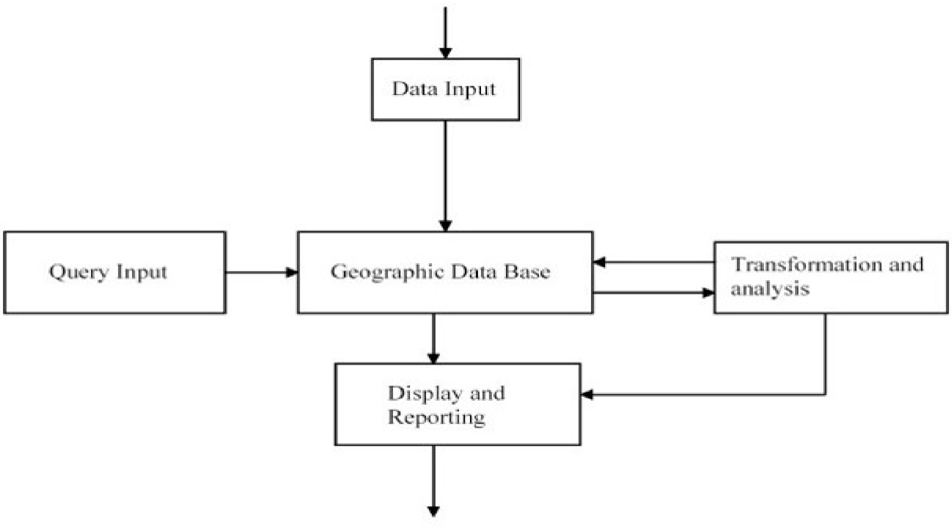

Figure 1. Components of computer-based GIS

A geographic information system is therefore a system dealing with geographic information about a particular space with a defined boundary. It combines technical and human resources with a set of organizing procedures to produce information in support of decision making, as shown in Figure 1.

1.3. Role

A GIS is required for creating awareness of environmental conditions for various applications including policy making. This involves the use of data. A GIS will, in general, have a means of inputting data into a database, editing the data, displaying information stored in the database, and performing certain calculations including sorting of the data in the database. The nature of the data stored and the analytical and modeling capacity of a GIS will determine the solution to particular problems related to floods or land use planning or other potential needs.

Data storage may be in a grid cell system or polygon system. In the grid system, the area of interest is broken up into square or rectangular grid pattern with data types and values associated with each grid cell. The polygon systems resulting from exact presentation of boundaries of areas, points, and lines is used to store maps at different scales or with different projections. The polygon system is extensively used in computerized cartography. The grid system, in which analytical procedures are handled on a cell by cell basis with differing data attributes associated with each cell, is superior to the polygon system.

Storage of terrain elevation data in a computer is a special case in spatial data management, commonly referred to as digital terrain model (DTM). In polygon-based systems, DTM involves storing every individual contour line. The triangulated irregular network (TIN) is a third technology that handles terrain data and provides features not available in the polygon or grid cell systems. In TIN, terrain is presented as a faceted surface with each facet being a triangular plane. Higher resolution is achieved by increasing the number of triangles in a given area. Data attributes to the triangles include soil types, river basins, land use, slope, aspect, and elevation.

Issues in spatial data management relate to resolution of database, generalization of the data, cost of storage, cost of retrieval, utility for analysis, ease of updating, and quality of geographical displays available with form of storage for each system (see *Use of Monitoring Data in Model Verification).*

The role of a GIS is to enable the capture, storage, and manipulation of data in a structured form, therefore allowing the use of analytical techniques on the spatial dimensions of problems. With a GIS, analysis and depiction of spatially referenced information as well as dissemination of results of analysis using thematic maps is possible. Environmental science and other disciplines have generated enormous amounts of data of many different types, and this is bound to increase in future.

A GIS is needed to store, display, and bring together data sets for improved data extraction and integration (see *Monitoring at Various Spatial and Temporal Scales*). Research can benefit from GIS-based data for modeling and simulation.

2. GIS Data Format

The spatial referencing systems allow recording and storage of various types of geographic information. The geographic entities or objects in a GIS are based on spatial and thematic data types. The spatial data types constitute geometric and topological data. The geometric data, which may be positional or shape data, are quantitative. They are used to represent coordinates and line equations. Topological data describe relationships among the geometric data and do not need to be stored explicitly since they can be derived from geometric data. Examples of topological relationships include connectivity, adjacency, and inclusion.

There are two categories of GIS data formats or structures: raster and vector. The two formats are used to geo-code land data on the basis of whether the data type is composed of point, linear, or aerial features. Most resource data is aerial and is encoded in a defined area in raster or vector formats. A GIS should be capable of using both raster and vector data since users have no control over the format of the data delivery.

2.1. Vector Format

Vector fields within a GIS involve the use of separate components of vectors: the length of unit vector along each of the relevant axes in two or three dimensions (distance) and magnitude. Cell grids and even polygons can be used to identify the location of vectors. Mapping between data models and data structures takes the form of polygons, TIN, contours, or point grids.

Vector-based systems convert feature boundaries to straight-sided polygons that approximate the original regions. The polygons are encoded by determining the coordinates of their vertices, which can be connected to form arcs. Polygons are then obtained by connecting the arcs. This is more accurate and requires less storage space than the raster format. However, the kind of format to employ depends on sources of geo-spatial data and type of output the user requires.

2.2. Raster Format

In raster format, it is easier to perform overlays and update operations than with vector data structures. Each grid cell is referenced by a row and a column number representing the type or value of the attribute of interest. When data are input into the GIS, the axis is aligned in the N–S direction and the origin is identified with the Universal Transverse Mercator (UTM) grid to facilitate referencing.

Raster or grid cell format is appropriate for data capture techniques like remote sensing, scanning of existing documents (maps or aerial photographs), and image processing in general. Mapping between data models for raster format takes the form of grid cells and point grids.

2.3. Database and Sources

Databases are the fundamental units over which information analysis can be performed (see *Statistical Analysis and Quality Assurance of Monitoring Data*). The main sources of geo-spatial data are: remotely sensed data from aerial photographs or satellite imagery, topographic maps, thematic maps, statistical information, and digital data which may require converting and importing (see *Monitoring of the Environment as a Whole*).

A database is a data collection of information about things and their relationships to each other. The four types of data entry systems commonly used in GIS are keyboard, manual digitizing, scanning, and importation of existing digital files with appropriate data exchange standards. To design the database, the important aspects are the boundary of the area, coordinates, number of data layers, features for each layer, attributes for each feature, and coding and organization of attributes. To manage the database, the spatial data must be put into real world coordinates by joining adjacent coverages.

Sources of remote sensing data for GIS applications in various environmental aspects include; LANDSAT, SPOT, NOAA, METEOSAT, and ground-based weather radar. Databases resulting from the joint use of several information maps can support a series of applications in different fields of environmental management and socioeconomics. Users select pertinent information for the different purposes.

3. Functionality of GIS

GIS functionality refers to the set of functions that a GIS can perform. The GIS provides the following set of capabilities for spatially referenced land related data and information: data input, data storage and retrieval, data manipulation and analysis, and data output and reporting.

3.1. Data Input

This function involves the identification and collection of data necessary for processing in the GIS as obtained from the various sources given in Section 2.3. These data are entered and verified using scanners, digitizers, and graphic displays driven by appropriate software. Part of the data input may also include format conversion, error detection, and topology construction.

3.1.1. Keyboard

Attributes data are commonly entered by keyboard during manual digitizing or as a separate operation in which the attributes are entered with a code to indicate the spatial element they describe. The attribute file is subsequently linked to the spatial data. Manual digitizing is the most widely used method for entering spatial data from maps.

3.1.2. Manual Digitizing

In manual digitizing, the map is affixed to a digitizing table and a pointing device is used to trace the map features. To digitize, data are registered on the digitizing table, then input into the GIS, transformed to standardized world coordinates, and finally, the various features are assigned attributes. The steps followed are:

(a) Preparing the map sheets. The features to include are marked in pencil.
(b) Digitize the coverage by moving the digitizer as accurately as possible along features.
(c) Identifying and correcting errors in digitizing.
(d) Define features and build topology by ensuring no overlap in features.
(e) Assign attributes to coverage features such as river names, vegetation types, and location information.

3.1.3. Scanning

A scan of a digital image of the map is produced by moving an electronic detector across the map surface.

3.1.4. Import of Existing Digital Files

This involves converting information using a computer text editor to create flat files that list a series of data coordinates. To produce a land use map, for example, classified remotely sensed imagery is used together with digitized topographic detail and point data from a flat file. Import of digital files allows one to combine classified data for a particular geographical area with other geographic referenced data sets for the same area.

3.2. Data Storage and Retrieval

The purpose of data storage and retrieval is to organize the data in a topographically structured form so that it can easily be retrieved for subsequent manipulation, analysis, and display. In addition to supporting multiple users and databases, security and data integrity are ensured.

3.3. Data Manipulation and Analysis

This functional component performs a number of tasks, mainly geometric calculations, map-overlay computations, network analysis, and production of estimates of parameters for transfer to external analytical models; all through user-defined rules (see *Analysis and Utility of Monitoring Data*). Through various operations, this function enables the use of spatial and nonspatial data contained in the GIS database to answer questions about the real world.

Stored map layers in the database need to be updated, edited, and manipulated for desired results. Analysis may involve overlaying several map layers, and selecting, retrieving, and extracting certain measurements from the data. These functions are performed by GIS system software commands.

By conducting a series of GIS processing operations, it becomes possible to answer queries for a GIS system. For example, the areas most prone to erosion when changes in vegetation cover are made within a watershed can be identified, and how much agricultural land or forest area will be lost when building a road by selecting alternative routes can be quantified. These queries and their answers form the basis for geographical data modeling in a GIS.

3.4. Data Output and Reporting

Output for all or selected portions of the spatial database are displayed using standard or cartographic formats (see *Regional and Global Geoinformation Systems*). Various hardware devices, such as plotters, displays, and printers, may be used for output presentation of maps, tables, and figures. Information is thus presented in a form suitable to the user, usually in either hard copy, "softcopy," or using electronic files or format.

Hardcopy outputs are permanent means of display. The information is printed on paper, photographic film, or similar material. Maps and tables are commonly output in this format. "Softcopy" output refers to viewing on a computer monitor. It may be text or graphic and in monochrome or color. Softcopy outputs are used to preview data before final hardcopy output.

Output in electronic formats consists of computer-compatible files used to transfer data among computer systems either for additional analysis or to produce a hardcopy output at a remote location. It is generally accepted that the output function of GIS must include dissemination of output information to users. Users must understand the GIS application tools and relationships between the available data and the required information. The user, the system, and the experts who advise on models and data involved in problem solutions constitute the GIS applications.

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Biographical Sketches

Christopher Misati Ondieki (Ph.D) was born on October 17th , 1955 in Kisii District, Kenya. He teaches in the department of Geography, Kenyatta University. He has also served as Hydrologist in various agencies. His research interests include extreme hydrologic events in humid and arid zones and GIS applications in environmental and socio-economic development.

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