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WORKSHOP ON REMOTE SENSING TECHNIQUES WITH APPLICATIONS TO AGRICULTURE, WATER AND WEATHER RESOURCES

(27 February - 21 March 1989)

CURRENT TRENDS IN GEOGRAPHICAL INFORMATION SYSTEMS FOR WATER AND LAND RESOURCES PLANNING

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LECTURE NOTES on:

CURRENT TRENDS IN GEOGRAPHICAL INFORMATION SYSTEMS FOR WATER AND LAND RESOURCES PLANNING

by

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1. INTRODUCTION

The collection and analysis of data concerning the spatial distribution of relevant characteristics of the earth surface have long been an important part of the activities of organized societies. From the earliest civilisations to modern times, spatial data have been acquired and rendered into pictorial (map) form to accomplish a variety of activities such as navigation, land survey and military operations.

In the last decades, the development of earth sciences disciplines (geology, geography, hydrology, soil sciences, etc.) and the ever increasing demand for a rational use of natural resources (water, land, mineral deposits, etc.) have greatly enhanced both the collection of spatial (georeferenced) data, and the production of a variety of general purpose (topographic) or special purpose (thematic) maps. Maps, indeed, are the best method for reducing very large-scale spatial relations so they can be easily perceived and analyzed (UNESCO, 1976; Nossin, 1977; Fraser Taylor, 1980).

During the 1960s, the advent and dissemination of high-speed computers and of data capture/display electronic devices, have profoundly influenced methods and techniques for map production, and a new discipline was set up: computer-assisted (automated/modern) cartography (cf. Fisher, 1979; Fraser Taylor, 1980; Monmonier, 1982; Shiryaev, 1987).

Meanwhile, scientists, planners and policy-makers have increasingly become aware of the importance of acquiring and using computer-based systems that enable any type of environmental data to be efficiently and cost-effectively handled, analyzed and displayed. Consequently, public and private agencies and scientific institutions made several attempts to extended to the realm of geographical data the methods used in processing tabular (non-spatial) data through Data-Base Management Systems (DBMS).

As a result, data-base systems for spatial data, commonly named Geographical Information Systems (GIS), were designed and developed which enable the acquisition, compilation, storage, updating, processing, analysis and display of spatial data, traditionally represented in the form of topographic or thematic maps. Hence, the main and unique features of a GIS consist in its capability of:

-a) capturing, handling and portraying the spatial characteristics of objects (geographical entities) from the real world;
-b) collecting and processing the non-spatial characteristics (attributes) associated to the these objects;
-c) identifying, analyzing and displaying the topological and geometrical interrelations existing between spatial and non-spatial properties of an object and of different objects.

1.1. Geographical Information Systems in Water and Land Planning

From the above, it is clearly apparent that the accomplishment of almost any project aimed at evaluating environmental resources and constraints may be greatly facilitated by the use of an efficient geographical information system.

This is particularly true when water resources assessment and their risk/benefit analysis constitute the primary concern of an investigation (cf. Haimes, 1980). Indeed, planning and management of water resources rely heavily on geological-geomorphological information about the river basin (Feldman, 1981). Topography, geomorphology, lithology, soil type and land use/cover are major determinants of a watershed runoff response. Land use/cover and topography of the floodplains are two basic factors controlling flood damage potential. Lithology, structure (tectonic evolution), slope instability and channel erosion play an important role on soil erosion, water quality/supply and hydropower potential (Cooke & Doornkamp, 1974; Feldman, 1981).

The collection of all these spatial data along with the traditional hydrological records (rainfall duration and intensity, river stages, etc.) allow gaining a comprehensive knowledge of the actual potentialities (water supply/quality, soil fertility, facility of transportation routes, etc.) and constraints (slope instability, erosion, flood and drought hazards) characterizing the project area (Feldman, 1981; WMO, 1985; FAO, 1986).

As an example of what previously stated, a short list of questions that can be answered by a GIS is provided:

-a) where is located reservoir "A" in region "B"?
-b) how large (area, perimeter, volume) is reservoir "A"?
-c) how many crop fields can be irrigated using reservoir "B"?
-d) what is the spatial distribution of rainfalls in region "B"?
-e) where and when flooding will likely occur in region "B"?
-f) what are the best actions against flood hazard in region "B"?
-g) what is the spatial distribution of soils in region "B"?
-h) what is the spatial distribution of population in region "B"?

-i) what are the spatial relations between soil fertility, flood hazard and population density in region "B"?
-j) what are the sites most suited for growing crop "C" in region "B"?
-k) where are the sites most suited for installing hydropower plants in region "B"?

As shown in the following sections of this report, some of the above questions can be readily answered by a GIS, others need many input data and a great deal of data processing, simulation and modelling; very few of them can find an answer using conventional methods.

1.2. Scope of the Report

Although the first achievements in the domain of geographical data electronic processing date back early to the 1970s, nowadays no general agreement does exists as yet on the techniques and methods associated with automating such a operation. Moreover, current computer technology, which is subject to such an explosive growth that the present state-of-the-art almost defies description, is being profoundly influencing the current approaches to and applications in the fields of automated cartography and spatial data processing.

Therefore, in the present report, an attempt is made to outline current trends in geographical information systems within the framework of water/land resources assessment projects, highlighting potentials and limitations of such systems.

Emphasis will be placed more on the operation and application of GIS than on the computer technology (hardware/software) required for their design and development. For a more detailed discussion on these technical aspects, the interested reader is referred to the excellent works by Nagy & Wagle (1979), Boyle (1980), Burrough (1986) and Shiryaev (1987).

Then, some problems related to the implementation of GIS in developing countries are briefly discussed, taking into consideration those hardware/software advancements that are likely to occur in a near future.

Lastly, as an example of the potential of GIS and digital cartography, a brief outline is provided of a current investigation, carried out at the Department of Civil Engineering of the University of Florence, which aims at developing automated techniques in drainage basin cartography and in assessing environmental hazards (Carrara, 1983, 1984, 1986; Carla' et al., 1987a, 1987b).

2. GIS BASIC CONSTITUENTS

Geographical information systems have three main components, namely: computer hardware, application software modules and a proper organizational context (Burrough, 1986). The complexity of each of these three components is dependent on the scope of the projects to be carried out, on the quality and quantity of data to be processed and, of course, on the amount of funds available.

In order to create multipurpose, nation-wide geographical/ cartographical date-bases, governmental (frequently military) institutions of many western world countries have recently developed large geographical information systems which are based upon very costly data capture/display devices and sophisticated software modules, and operated by large groups of technical, scientific and managerial personnel (Fraser Taylor, 1980).

On the other hand, small private firms or research institutions are currently involved in projects aimed at implementing small GIS on relatively low-price hardware environments through the use of software packages tailored to exploit to the maximum the ever increasing, but still limited, capabilities of 16-bit microcomputers.

Besides the problems related to the the choice between a large or small GIS configuration which will be later discussed, the fundamental hardware components of a GIS can be summarized as follows (Fig. 1):

- central processing unit (CPU);
- disk drive storage unit;
- tape drive storage unit;
- visual (graphic/alphanumeric) display unit;
- data capture (digitizer/scanner) unit;
- data output (printer) unit;
- data drafting (plotter) unit.

Although it is possible to set up a GIS on any kind of host computer, potential users should be aware that, when running a GIS under time-sharing on a main-frame, interactive responses may be extremely slow. Then, the choice of a stand-alone minicomputer (with 5 Mbytes of central memory and at least 300 Mbytes of disk memory), is highly recommended (Burrough, 1986).

Data capture and drafting devices, which constitute the most specific features proper of a geographical information system, may greatly vary in term of performance (and cost) from simple digitizing tablets to electronic raster scanners, and from a small desk plotters to flatbed, optical head drafting devices. Likewise, visual display units (VDU) may vary from simple, low-cost terminals to microcomputers incorporating special hardware for high-resolution and quick display of data.

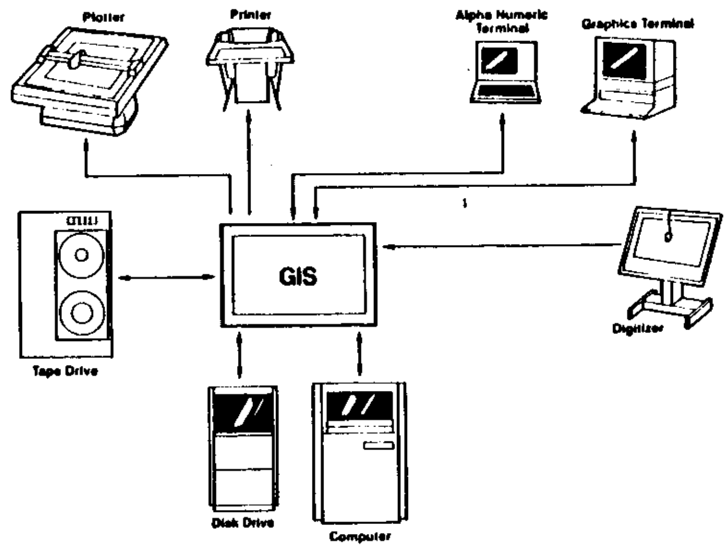

Fig. 1. Main hardware components of a modern Geographical Information System.

As far as software is concerned, the main modules for a GIS regard the following operations:

- data input and verification;
- data storage and management;
- data processing and analysis;
- data output and display;
- GIS-user interaction (query input).

The main task of data input programs refers to the conversion of source data in the form of existing maps (or photographs) into a computer-compatible digital format. Clearly, such programs are highly dependent on the characteristics of the devices available for performing this operation (digitizers, interactive visual display units, scanners, etc.).

Although data storage and management modules are derived from traditional (non-spatial) DBMS, they differ from the latter, being able to maintain a clear linkage between the spatial (topology and geometry) and attribute (rock/soil composition, crop production, etc.) components of each geographical entity.

Data transformation (processing) and analysis programs embody a large set of sub-modules aimed at performing a variety of operations ranging from coordinate transformations to map overlay.

Data display programs must be highly sophisticated where standard (topographic) map production constitutes one of the main targets of GIS operations.

The last module of GIS software is absolutely essential the acceptance and use of any information system. Today, most GIS are provided with an easy-to-learn and easy-to-use menu-driven command language enabling the interaction between the system and the user.

From the above short outline of GIS hardware and software components, it is apparent that geographical information systems have a lot in common with the nowadays very popular computer-aided design (CAD) systems. Both systems have graphic data entry and display capabilities. The main differences lie in the fact that the former systems can handle efficiently much greater data volumes and, most importantly, have much superior data processing/analysis capabilities. Hence, CAD-derived systems, which are available on the market for comparatively low prices and frequently sold as map analysis tools, are not recommended for performing geographical analyses.

Today, many reliable, high-quality GIS packages are present on the market, many run only on dedicated hardware ("turn-key" systems) such as INTERGRAPH, SYNERCOM, SYSSCAN, etc.; a few are virtually machine independent (ARC/INFO). Both types present advantages and pitfalls in terms of overall cost and performance.

The interaction between GIS system and personnel (technical, scientific, managerial) incharged to run it constitutes a problem of paramount importance. Many state or private organizations, which spent a large amount of money in buying GIS hardware and software, but did not invest adequately in training personnel or hiring skilled individuals, did not succeed in making their system operational. This problem may be particularly crucial in developing countries where few people are familiar with the technical aspects of a discipline as new and complex as geographical data processing.

Consequently, before starting a project involving the acquisition and implementation of a geographical information system, a carefully-designed strategy must be set up. This should cover the following aspects:

-a) definition of the purpose for which the GIS is developed (land reclamation of a small district, irrigation or soil conservation of a large region, rural or urban planning, hydropower design, water quality assessment, mineral exploration, etc.);

-b) identification of actual/potential users of the system (governmental, private, scientific institutions, etc.;
-c) assessment of the total costs involved in acquiring, implementing and running the system (they may range from less than 20,000 to over 200,000 dollars);
-d) selection of the hardware/software environment which is most suited for the type of applications intended;
-e) recruiting (or retraining) personnel with technical, scientific and managerial skills that permit solving the very many and different problems related to GIS operation activities.

Experience from several cases of GIS-project failures demonstrated that, if one or more of the above issues has not been clearly set up, the geographical information system will never become operational with great loss of money and frustration of the organization involved.

3. PHASES OF GIS DEVELOPMENT AND APPLICATION

In any project aimed at developing and using a GIS, the following broad phases can be singled out, each of which is characterized by different levels of complexity, time consumption, technological investment, and involvement of different specialists.

- i. data acquisition
- ii. data encoding/digitization
- iii. data processing
- iv. data display/analysis

In the following sections of this report each phase of GIS development will be briefly treated separately, however they actually constitute a continuum of a global and integrated process.

3.1. Data Acquisition

The definition of the type (rock, soil, vegetation covers, topography, surface and ground water, etc.), quality (highly to poorly reliable) and quantity (from few measurements scattered over a large region or throughout a long period of time, to a large data set collected in a small area) of the environmental data, which have to be collected and entered into a GIS, must represent the first goal in any land and water-resource assessment project.

Indeed, too frequently sophisticated geographical information systems have been developed, implemented and employed to process almost useless (but easy to gather) environmental data.

Depending on the nature of the project, size of the study area and time/funds available, data collection can be accomplished through the following procedures:

-a) field surveys/measurements;
-b) aerial-photography;
-c) digital remotely-sensed imagery;
-d) existing cartographic (map)/tabular data.

At present, in western world countries existing maps are the main source of data for a GIS. Conversely, in many developing countries existing map coverages are scarce or constituted by old, poorly reliable documents: hence, data collection must start from field surveys and aerial-photography interpretation. However, the new polar or geostationary, satellites provide digital high-resolution, imageries which may become or will become the primary source of data for a GIS for projects in both developed and developing countries.

3.2. Data Encoding and Digitization

This task has always constituted a very time-consuming, tedious and error-prone step. However, recent advancements in graphic entry devices have made it possible to reduce significantly the time involved in this operation, and to increase greatly the precision and quality of the digitized data.

In terms of decreasing data entry complexity, data sources can be conveniently grouped and ordered into three broad categories (Nagy & Wagle, 1979):

-a) spatial (pictorial/graphic) data (aerial photographs and topographic, geological, soil, land-cover maps, etc.);
-b) non-spatial (attribute, alphanumeric) data (census or crop reports, field notes, and tabulation of historical meteorological or hydrological data, etc.);
-c) remotely sensed data (LANDSAT, SPOT, etc.) in digital form (land-use, land-cover, etc.)

Depending on the hardware facilities available, digitization of spatial data (entities), which can be reduced to only three basic classes: a) points, b) lines, and c) areas, is performed:

-a) semi-automatically (lines, points and areas are digitized and labeled with the aid of a free cursor digitizing table that is connected either to the host computer or to a microcomputer);
-c) automatically (today by means of highly sophisticated electronic raster scanners).

When digitization is performed semi-automatically, a great deal of errors may be generated. For example the boundary between two regions can be digitized twice leading to topological errors known as "slivers" and "gaps". The boundary of a region may be incomplete or makes inadmissible loops. Similar problems can arise with network structures: two or more links may not meet in a node leading to a loss of connectivity. In addition, during the "labeling" phase geographical entities may be assigned a wrong identifier or improper non-spatial attributes. As later discussed, many digitizing errors can be corrected by the system during the storage/editing phases.

Where digitization is made automatically, most of the above pitfalls are overcome; hence, this approach appears to be the most promising, although still extremely costly (Boyle, 1980; Shiryaev, 1987).

As previously mentioned, each geographic entity (point, line and area) is characterized by a spatial (geometric) component (location and shape/topology) and by a non-spatial (attribute) component.

Although attribute data can be attached to each geographic entity during the digitizing phase, it is not efficient to enter large numbers of complex non-spatial data interactively. In general, it is better to assign attribute data to the spatial ones after their digitization.

Since satellite data are already in digital form (in raster format), their entry does not require any digitizing operation. However, complex and still unsolved problems rise when satellite imagery has to be exactly referenced (aligned) to the topographic map data to ensure geometrical/topological compatibility with other data set of the data-base. Indeed, satellite images are usually affected by several geometrical and radiometrical distortions which need to be corrected by means of various techniques that belong to the family of the so called "image processing techniques".

3.3. Data Processing

Data processing includes the following main steps:

-a) data storage: includes the keying onto computer compatible media (tape/disk/diskette, etc.) of data and their storage into a data-base.
-b) data editing: incorporates all the operations aimed at checking and validating the quality of data entered, today through interactive operations on a VDU.
-c) data manipulating: refers to the assemblage of "routine" procedures for standardizing data units, recoding/reclas-

sifying values of attributes, calculating derived parameters, modifying/transforming scale or projection system of maps, infilling missing data, interpolating, aggregating and modeling.

-d) data updating: concerns the procedures for adding new data to the existing data-base or replacing old data with new ones.

-e) data retrieval: regards the selection of data/spatial entity subsets from the main data-base by the spatial or attribute component of geographic entities.

3.3.1. Data storage

When data have been digitized, they can be stored into computer data-base for their handling, manipulating and analysis. Among the different data-base organizations (hierarchical, network and relational) originally designed by computer scientists for running non-spatial DBMS , the relational one seems to be the most suited for geographical analysis. At present, the most recent GIS packages are generally based upon relational databases.

At this stage of the operation, it becomes of paramount importance the definition and selection of a geocoding system, where the term refers to the assemblage of procedures aimed both to represent the dimension of space in terms of computer storage, and to convert data measurements to a format compatible with the spatial representation selected.

There are different methods for geocoding geographical entities (points, lines and areas); however all of them imply two fundamentally different types of data capture/storage, namely:

-a) raster (grid, cellular): firstly, land surface is divided into a matrix of cells by means of a uniform rectangular (usually square) grid (raster) referenced to some appropriate system (Universal Transverse Mercator Projection (UTM), etc.); secondly, each cell is labeled with the attribute of the geographic entity which is spatially dominant within the cell; hence each geographical entity is explicitly represented by a set of cells (pixels) labeled by a certain value/symbol/color;

-b) polygonal (vector, stream): points, lines, areas are spatially identified by means of a set (stream) of x-y coordinates (vectors) referenced to some system (latitude/longitude, UTM, etc.); hence, each geographical entity is implicitly represented by a set of vectors linked together by a set of connectivity rules.

Nowadays relative advantages and disadvantages of these two geocoding approaches are well known; they regard: map accuracy, data storage/retrieval efficiency, quality and aesthetics of graphical display, and cost and time for development and implementation.

Advantages of grid models can be summarized as follows:

-a) terrain attributes are stored as matrices which can be easily handled and up-dated by computers;
-b) information is in a suitable form for statistical analyses, simulation and modeling;
-c) development and implementation of this type of system does not involve an extremely large amount of money and time;
-d) the integration of mapped data with remotely sensed data is very easy.
-e) this model has been widely used and tested by many governmental and private institutions.

Drawbacks of grid models are:

-a) map accuracy is directly dependent on the grid size used. The latter, on its turn, is controlled by factors such as computer memory available and size of the area to be investigated; hence, generally data volumes are very large;
-b) they are unsuited for handling and displaying linear data (drainage network, road systems, etc.);
-c) aesthetics of map display is generally low.

Advantages of polygonal models refer to the fact that:

-a) they can process any type of data (lines, points and areas);
-b) they permit significant data compression to be made.
-c) they can efficiently describe the topology of any geographical entity with network linkages;
-d) they can provide high-quality graphical displays;

Drawbacks of polygonal models are:

-a) software development and data processing/analysis are very complex and costly;
-b) combination of several maps (layers) though overlay operations requires very efficient and complex algorithms;
-c) simulation and statistical analysis cannot be readily performed;
-d) although current trends in GIS technology indicate a gradual change from raster to polygonal models, up to now few polygonal systems have been actually developed, implemented and, most importantly, thoroughly exploited.

In the light of the experience acquired during the past ten years, it can be stated that both the raster and vector representations of geographical data are equally valid.

Hence, today the main issue seems to be how to move quickly and accurately from one to another. Indeed, where routines are available for an efficient conversion from raster to vector and vice versa (although at present the latter is much more complex and less satisfactory than the former), data processing, retrieval and analysis can be carried out using the structure that is most suited in performing that specific task.

Regardless the data capture/organization (raster or vector) selected, any well-designed GIS should fulfill the two fundamental, somewhat conflicting, requirements:

- i. efficient storage of spatial component (data compression);
- ii. faithful preservation of input data resolution.

A short outline of the storage techniques for raster and vector structures follows.

3.3.1.1. Storage and data compression in raster structures

In order to organize efficiently raster (and vector) data regarding two or more land attributes (topography, soil, geology, etc.), each attribute is usually stored as a separate "overlay" or "layer" or "plane" (Fig. 2, 3).

In addition, data in raster structure can be organized in very different ways; the most common are those where: a) each cell of each layer is referenced directly; b) each layer is referenced directly, c) each map (set of layers) is referenced directly (Burrough, 1986).

At present, all these three types of structures are used in raster-based GIS packages available on the market.

Then, different techniques can be used to reduce to the minimum the computer space needed to store (raster) data into the data-base. These techniques, named "data compression" techniques, have been long investigated by computer scientists. Some of them are applied at the time of digitization (for example, absolute coordinates are replaced with relative coordinates); other methods concern the data storage itself, namely: a) chain codes; b) run-length codes; c) block codes; d) quadtree codes (cf. Rosenfeld, 1980).

It is worth stressing out that all these methods present some drawbacks at the stage of data processing and analysis, being these operations much more complex when carried out with data in compact form.

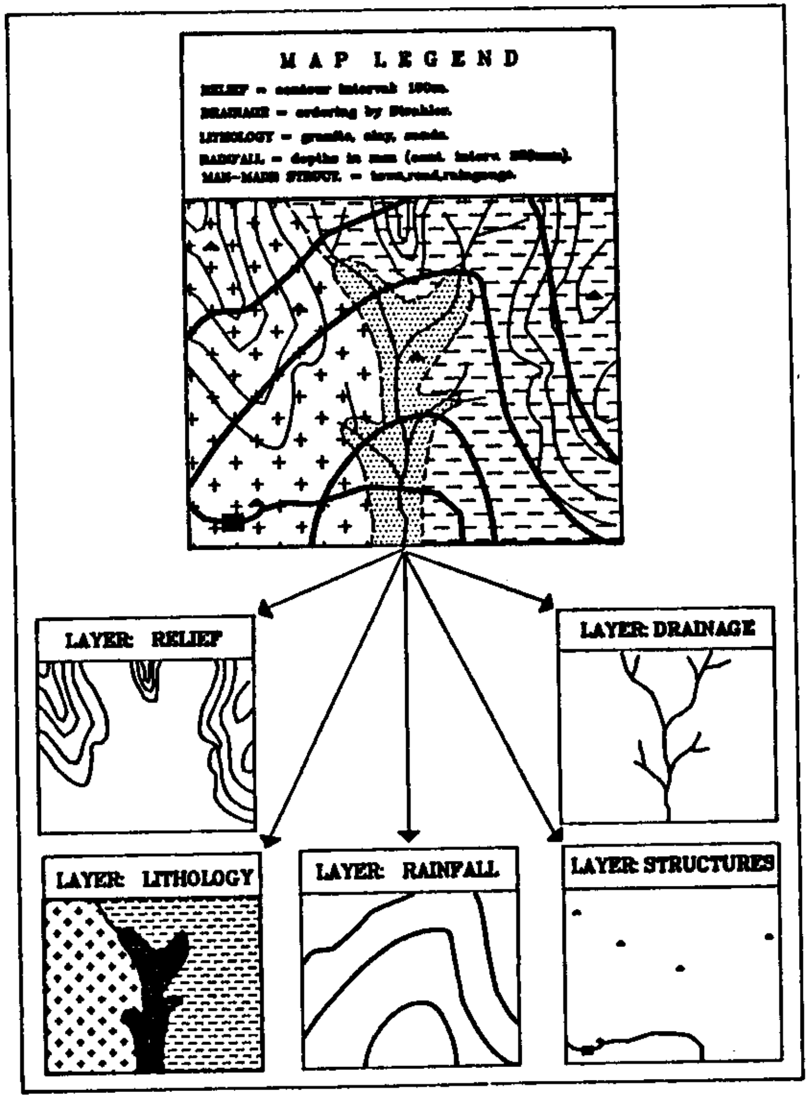

Fig. 2. Example of map displaying different geographical entities, each one portrayed on a separate layer (plane).

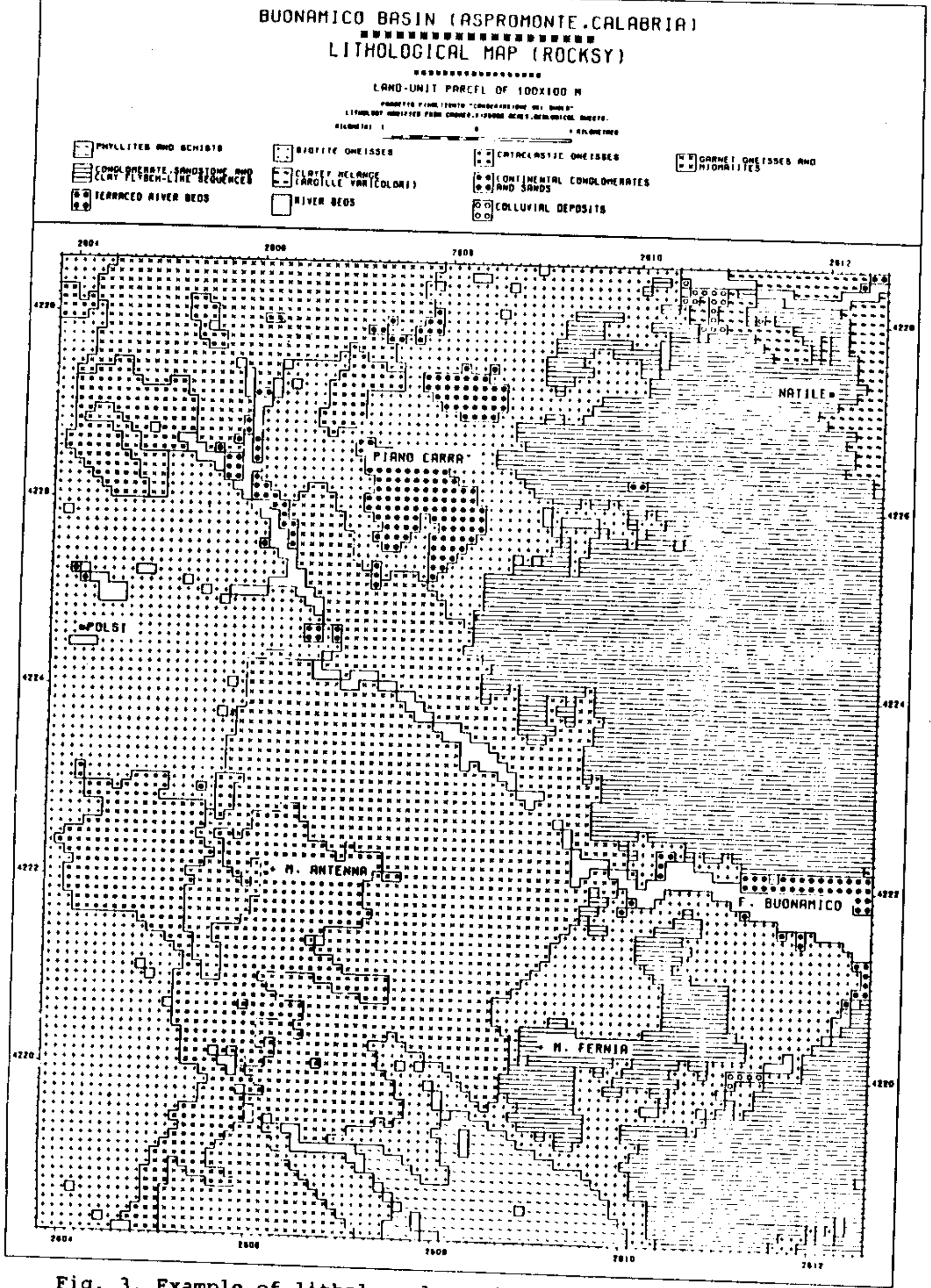

Fig. 3. Example of lithology layer based on raster structure.

3.3.1.2. Storage of vector data structures

There is no single, preferred method to organize and store vector data. A large set of different procedures are at present used, each one characterized by advantages and disadvantages. However, all of them attempt to:

-a) store all the data in a minimum space;
-b) define the topological properties of each spatial entity;
-b) link the geographical and the attribute components of each spatial entity.

In order to know the topology of each entity, it necessary to explicitly define:

- its shape, length (for lines) and perimeter/area (for areas);
- its connectivity (for lines) or neighborhood (for areas);
- its hierarchy (for lines and areas).

Vector (or raster) data structures of lines (roads, power-lines, drainage networks, etc.) require a data organization where each line (chain, string) is connected to the others through nodes carrying the connectivity information.

Vector structures of areal (polygons) entities (crop fields, rock units, etc.) may vary significantly; the most common are:

-a) simple polygons;
-b) polygons with point dictionaries;
-c) polygons with explicit topological structures.

Since boundary lines between adjacent polygon have to be digitized twice, simple polygonal structures may lead to several errors ("gaps", "slivers", "dead ends", etc.) which seriously hamper subsequent data processing and analysis. In addition, with this structures there is no neighborhood information, nor control on the correctness of topology. Virtually all CAD systems or mapping systems derived from CAD technology use this type of structure.

The second and particularly the third organizations (point dictionaries and explicit topology) permit avoiding or correcting such errors, and enable connectivity and neighborhood to be preserved or checked. Both are suitable for and in agreement with the requirements of spatial analysis. Today, any efficient vector-based GIS should incorporate such a type of data organization (Burrough, 1986).

3.3.2. Data Editing, Manipulating and Updating

When data have been efficiently stored, the subsequent processing step concerns their verification, correction, manipulation and updating. Today, some of these operations are performed interactively (moving/rotating entities, etc.; see Tab. 1), others can be accomplished semi-automatically or automatically (joining/edge matching, etc.).

It is worth pointing out that the verification and correction of data improperly digitized may constitute a very long and frustrating operation. Hence, efficient and flexible editing capabilities must be built into the system. Indeed, such capabilities (some of which are listed in Tab. 1) should constitute one of the most important features of a modern geographical information system.

Tab. 1. Some GIS capabilities of data editing and manipulating.

ADD/DELETE/CHANGE	Interactive editing of alignment, length, text, and attributes.
MOVE/ROTATE	Move an entity to a new position.
STRETCH/RECTIFY	Adjust coordinates to fit a true base.
TRANSFORM SCALE	Adjust coordinates to match a given scale.
TRANSFORM PROJECTION	Adjust coordinates to match a given projection.
ZOOM/WINDOW	Enlarge/reduce area of attention
CLIP	Cut out area of attention as a separate projection.
JOIN/EDGE MATCH	Join two or more adjacent maps ensuing continuity of lines across the join.
CLEAN	Remove digitizing errors as "gaps" and "slivers" in polygons or networks.
OVERLAY AND MERGE	Intersect two or more layers to create a new one.
GENERALIZATION AND SMOOTHING	Data reduction changing scale and removal of excess coordinates.
RASTER TO VECTOR	Convert raster data to a set of lines (and points).
VECTOR TO RASTER	Convert line and polygon data to grid structure.

3.3.3. Data Retrieval

Unlike CAD systems, true geographical information systems provide a large set of tools aimed at retrieving data through:

-a) the geometric component of each geographical entity,
-b) the attribute component of each geographical entity.

Generally, Boolean algebra, which uses AND, OR XOR and NOT operators (Fig. 4), is the most common tool for retrieving subsets of data characterized by specific attribute values or by certain geometrical properties. While the first operation is common to any data-base, the latter is a unique feature of a GIS.

Boolean operators are also used for "overlying" (crossing/intersecting) different map layers. The intersection of two or more maps constitutes on of the most popular operations in GIS application. This task, which has long occupied the attention of computer cartographers, cannot be readily performed when data are organized in vector format. Indeed, if the maps contain many polygons, their overlay can result in the generation of a very large number of small polygons (Fig. 5). Some of which may constitute very significant entities for the scope of the investigation, while others are seemingly unimportant and need subsequent filtering or merging operations.

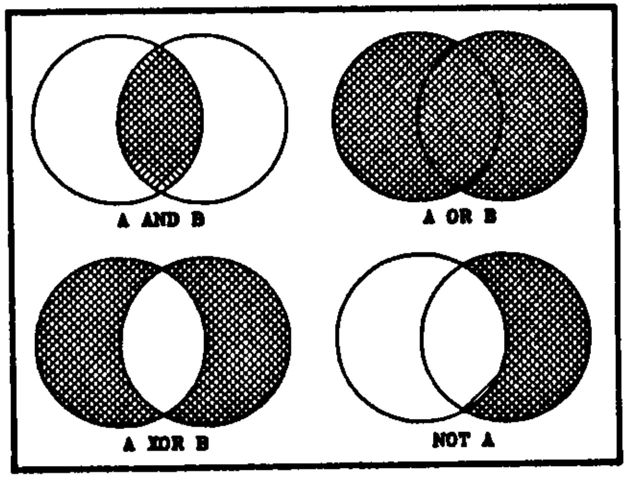

Fig. 4. Venn diagrams showing the results of applying Boolean logic to the intersection of two sets (maps). The shaded area of each diagram is "true".

Another problem related to map overlay in vector format refers to the very heavy computing demands when searching for intersections of polygon boundaries of the two maps.

As previously stated, such problems virtually do not occur when map overlay is carried out using raster data structures.

Regardless the type of data structure used, map overlay may produce a new map with too many attribute values. For example, by intersecting two simple maps, each one displaying an attribute with 6 values, the resulting new map may have up to 36 attribute values assigned to countless small polygonal regions; hence, the need to carefully reclassify the attributes values of each source map before intersecting them.

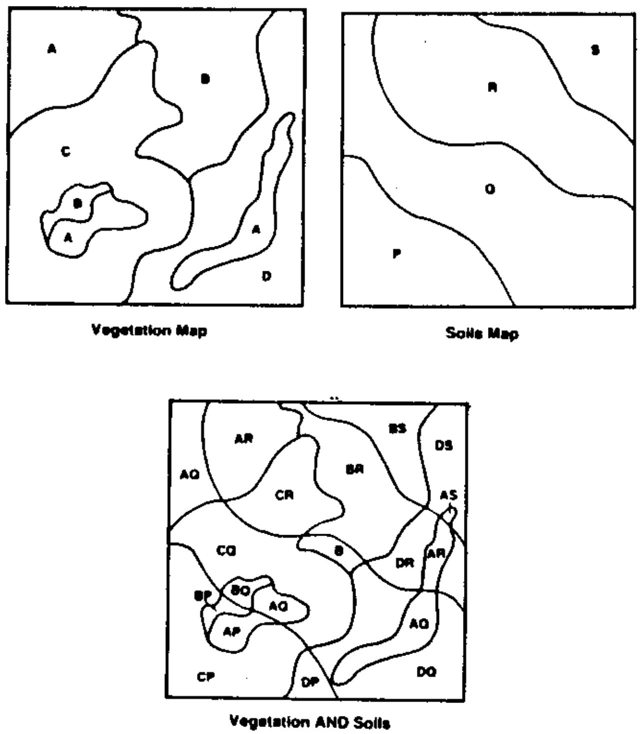

Fig. 5. The result of overlying (map "intersection") two simple maps (vegetation and soil map) to create a new one, using Boolean "AND" operator. Many small new polygons are created.

3.4. Data Display/Analysis

While in traditional cartography map drafting constitutes the final and "irreversible" phase of the map-making process, with GIS computer-aided cartography the user can readily modify map display. In fact, information occurring on maps is in a suitable form for further automatic treatment by contouring, filtering, interpolation methods which may facilitate readability and interpretation of map content.

Hence, in a geographical information system analysis and display become a strictly interrelated process.

3.4.1. Data display

Nowadays a large variety of output devices are available, each one may be particularly suited in performing a specific task and in meeting certain requirements of the user. Until recently display or drafting units have been very expensive; however, at present their prices are starting to fall down making them affordable to a wider range of users. The most commonly used are :

-a) line-printer (for low-cost, gray-scale printouts);
-b) incremental/step (with multicolored pens) plotter (for medium/high-cost, high-quality drawings);
-c) matrix (b/w or color) plotter (for medium/high quality, medium/high-cost drawings);
-d) ink-jet plotter (for medium/high-cost, medium/high-quality/ full-color drawings).
-e) Video Display Unit (VDU)/Cathode-ray tube (CRT) (for temporary display, interactive data editing and analysis).

Through the above devices, it is possible to display data on:

- temporary maps on a VDU;
- maps of low/intermediate quality on paper;
- final maps of high quality on paper or photographic negatives.

Temporary maps, maps portrayed for but a short period of time on CRTs, or enhanced imagery resulting from the machine processing of different sources of data and information are (or will be) the result of these new cartographic procedures. Medium-quality maps are common used for data checking, verification and analysis. The final maps, then, can be drafted on paper by means of flatbed/ drum pen/scribe plotters, or directly on photographic negatives through the use of highly sophisticated optical head devices.

3.4.2. Data analysis

Since data analysis in highly dependent on the type of investigation that each user has to carry out, only some general statements are provided here.

Among the many and different types of analyses, which can be carried out on the data stored into a GIS, the most common ones fall into the following broad categories:

-a) spatial analyses;
-b) statistical analyses;
-c) classification/generalization;
-d) modeling.

3.4.2.1. Spatial analysis

Efficient geographical information systems should enable a large set of spatial analyses to be performed.

As previously outlined, one of the most common GIS capabilities refers to the so called "map overlay analysis". This operation consists in the intersection of two or more layers, usually using Boolean logic and attribute reclassification, in order to produce a new one. The derivative maps obtained in this way can display selected land features which may help the user in a variety of investigations (assessment of environmental resources and constraints; route design; etc.).

Another type of spatial analysis refers to the realm of neighborhood analysis. Through functions, which make use explicitly of the spatial association of the geographical entities, several tasks can be performed, among which:

- assign to a map unit a value according to the values of the neighboring units within or beyond a given distance in order to create a new map;
- find shortest route two points on a continuous surface or the shortest path along a network in terms of time, cost distance, etc.;
- generate a continuous surface from point data.

The first operation finds application in fields such as waste disposal site identification, flood risk computation, etc.; the second is commonly used in route or powerline design; the third constitutes a very important and widely used operation, commonly named "interpolation".

3.4.2.2. Interpolation

When dealing with point data (namely, rainfall stations, well points, etc.), in order to produce thematic maps it is necessary to apply some interpolation procedure which converts point data to spatially continuous data: a problem which has long been investigated (Davis, 1973; Agterberg, 1974; Whitten, 1975).

This task may be accomplished by means of various well-known methods; however, as stressed by all the experts in these methods, they should be selected and used with great care, all of them being highly dependent on the type of data, density of control points, and scope of the investigation.

When dealing with discrete (categorical) data (geology, vegetation, soil, etc.), interpolation can be performed only by drawing abrupt boundaries to delineate regions with different attribute values (stepped model of choropleth maps). A second boundary interpolation technique is that based on Thiessen polygons, which finds wide application in producing rainfall depths maps.

When dealing with spatially continuous data (elevation, population density, etc.), interpolation techniques imply a model according to which the attribute in question can be described by a mathematically defined surface. Techniques for interpolating continuous data can be grouped into two main classes:

-a) global fitting: a model is constructed from all observations of the attribute of interest at all points in the study area; examples are:
  - polynomial trend-surface analysis;
  - Fourier series.
-b) local fitting: each value estimate is based on the values of the attribute from the neighboring points only; examples are:
  - splines;
  - moving averages;
  - kriging;

Both approaches present advantages and disadvantages. In the global fitting local features are not well accommodated, while long range variations are clearly identified. In local fitting, conversely, local anomalies are accounted for without affecting the values of the other point on the surface.

As far as moving averages are concerned, it is worth noting that some techniques appertaining to this class attempt to interpolate point data using an "adaptive" procedure which interpolates each point using the algorithm most suited to the specific conditions of its neighborhood (Clarke et al., 1982).

As later discussed in detail, one of the first applications of this method regards the generation of high-fidelity digital terrain models from contour maps (Carrara, 1986).

3.4.2.3. Statistical analysis

Advanced statistical capabilities are not a common feature of a GIS; on the other hand, such operations can be readily performed interfacing a GIS with one of the many statistical packages available on the market (SPSS, SAS, BMDP, etc.).

Since a discussion of the statistical methods is beyond the scope of this report, here it will suffice to remember that the most common statistical techniques that can find application on the spatial and non spatial components of geographical entities are:

-a) univariate statistics;
-b) multivariate statistics.

The first allow describing in a systematic and ordered form all the data under study through the drawing of frequency distribution graphs of each variable and the calculation of the related point estimators (mean, variance, standard deviation, etc.).

Among the latter, factor analysis, cluster analysis and discriminant analysis play an important role in map classification and land/water resources modeling.

One of the few examples of the potential of integrating GIS capabilities (map overlay analysis) and multivariate statistics (discriminant analysis) is provided by an investigation carried out in the Petrace basin (Southern Italy). Scope of the study was to assess the suitability of oliveyard cultivation in the basin. To accomplish this task, 20 land attributes were collected (geology, geomorphology, land-use/cover, etc.), encoded, digitized and stored into a in-house developed raster GIS. Then, through map overlay and discriminant analyses an environmental-based statistical model was built up, according to which each grid-cell of the region was assigned a value (score) reflecting its suitability for growing olive trees (for detail about method and result, see Bottero et al., 1985).

3.4.2.4. Classification

Classification of geographical attribute data plays a central role in data analysis. Indeed, without classification or generalization map readability and interpretation is difficult or impossible. A variety of methods has been proposed or used to group into classes the values of a map attribute. Class intervals may be chosen (cf. Burrough, 1986):

-a) with respect to specific aspects of the data set under study (idiographic); an example is the class limits dividing a multi-modal frequency distribution of a sediment sample;
-b) in direct mathematical relation to one another (serial); examples are equal interval arithmetic classes or classes defined as a proportion of the standard deviation of the frequency distribution of a population density;
-c) according to threshold values that are relevant to, but not derived from, the data set (exogenus); an example is given by the slope classes used in many geomorphological maps.

It is worth noting that the way according to which a land attribute has been classified may exert a great influence on the subsequent analysis and interpretation of the data under study. Hence, it is strongly recommended to carefully design a strategy before performing any classification of the data collected.

Frequently, in geographical analysis map units have to be classified on the base of two or more attributes measured for each unit. In this case, multivariate techniques (factor, cluster and discriminant analyses) become an essential aid to accomplish the task.

Lastly, recent developments in <u>expert systems</u> point out the possibility that in a near future the user will be able to classify maps with the aid of a system which:

-a) incorporates, in the form of formal logical statements, previous information and experience derived from experts in that specific discipline;
-b) makes full use of the geographical data stored in the database for answering a variety of questions.

The next Chapter will deal with an application of the potential of geographical information systems, which during the past decade has occupied earth scientists and cartographic agencies: the generation and application of <u>digital terrain models</u>.

4. DIGITAL TERRAIN MODELS

It has long been known that a wide spectrum of geomorphological, hydrological and cartographic problems can be solved by the use of digital terrain models (DTM), where this term refers to the body of data and information made up of earth surface elevations both known at defined locations (usually regularly spaced) and predictable at any other location by means of an interpolation function (cf. Stefanovic et al., 1977).

From a digital terrain model it is readily possible to derive a large set of morphometric (such as: slope gradient, aspect, vertical (downslope) convexity, horizontal (across-slope) convexity, etc.) maps that find wide application in the fields of theoretical/applied geomorphology and hydrology, agriculture, civil engineering, and urban or rural planning.

In almost every branch of the hydrologic investigation terrain geomorphometry plays a basic role, among which:

-a) flood control (flood frequency and duration, spillway discharge, reservoir storage, channel and floodway capacity, water surface elevations, flooded areas computations, etc.);
-b) water supply and quality (rainfall and snowmelt frequency and duration, reservoir storage, pollution control, etc.);
-c) hydropower design and control (powerplan and minihydro location, reservoir identification and analysis, etc.).

In addition, a DTM can constitute one of the most important data input for various computer programs (many of which already available on the market) that are able to perform a large variety of tasks, among which:

- block diagrams, profiles and horizons;
- volume estimation by numerical integration;
- contour maps;
- line of sight maps;
- maps of slope, aspect, convexity and concavity;
- shaded relief maps;
- drainage and divide networks delineation.

Consequently, during the past decade governmental and private cartographic agencies have attempted to generate DTM for large regions or whole countries using a variety of manual, semi-automatic and automatic techniques. However, only in the late seventies computer technology (hardware/software) has made it possible to acquire, process and display elevation data efficiently and cost-effectively, through the application of sophisticated electronic raster scanners, interactive graphic workstations and plotters (Boyle, 1980; Leberl & Olson, 1982).

4.1. Generation of Digital Terrain Models

Today there are different methods and techniques to obtain a digital terrain model:

-a) where detailed topographic maps (ranging in scale from 1:5,000 to 1:50,000) are available, data acquisition can be carried out through digitization of contour lines or sampling along profiles or grids on the maps; then, by means of an efficient interpolation program, the strings of elevation coordinates can be converted into a regularly spaced grid network, namely, an altitude matrix or raster/grid DTM;
-b) a more accurate way for producing an altitude matrix consists in the use of aerial photographs; in this case it would be possible to achieve a much higher degree of spatial resolution. However, a great deal of time and a computer-supported stereoplotter are necessary;
-c) for some specific investigations, such as transportation routes design, triangular-based elevation models (TIN) have been selected and used, since elevation control points are directly measured on the ground by means of topographic surveys.

Regardless the method selected in producing a DTM, the choice of the spatial resolution of the elevation point sampling is of great importance for actual and potential applications.

According to the size of the area investigated, its geological-geomorphological setting and the scope of the study, altitude matrices with a point spacing (cell size) ranging from 50x50m to 100x100m have to be produced. The finest resolution showed to be adequate for any type of investigation. The coarsest one demonstrated to be appropriate mainly for medium-scale (1:100,000 to 1:250,000) land evaluation studies.

Nowadays, where dealing with large areas, the best method for generating a grid DTM consists in digitizing contour lines by means of an electronic raster scanner and by interpolating contour lines through an contour-specific interpolation algorithm. This trend is presently followed by many countries (U.S.A., U.K., Sweden, etc.). In Italy, for example, the Military Cartographic Institute (IGMI) is undertaking a major project aimed at digitizing contour and drainage lines from 1:25,000 scale topographic maps - which cover the whole country - by using electronic raster scanner technology (Ammannati & Grassi, 1982).

A crucial step in the procedure concerns the method by which DTM elevations are interpolated; many different interpolation algorithms have been proposed or implemented (cf. Clarke et al., 1982); however, few or none of them appear to provide true high-fidelity elevation grid-data.

4.1.1. High-fidelity DTM from contour lines

In order to illustrate the potential in hydrology of digital terrain models and geographical data processing, a short outline of a long-term investigation currently carried out at the Departement of Civil Engineering of the University of Florence follows.

This investigation is being developed within the framework of two different nation-wide projects: the first aimed at assessing the potential of hydro-power resources of some Italian regions; the second oriented towards the control and the prevention of natural geologic-hydrologic catastrophes (Carrara, 1986; Becchi & Giuli, 1987; Carla' et al., 1987b).

As part of this study, the quality of the data obtained by digitizing, with an electronic raster scanner, contour lines and drainage networks of topographic maps, was tested. Then, a new procedure for generating high-fidelity, grid-based, digital terrain models, starting from digitized contour lines, was set up. Lastly, an attempt was made to automatically identify stream lines and related divides and determine the main geomorphological and hydrological parameters of a watershed.

As shown in the flow-chart of Fig. 6, the different phases of the investigation have required the use of different hardware resources: some of which were provided by governmental cartographic institutions (such as the very costly raster scanner system), others were already available or specifically acquired (mini/microcomputers, incremental plotter, graphic workstation). By carefully integrating these resources, it was possible to develop a set of procedures for the accomplishment of the study.

The new technique for generating a grid DTM form contour lines, named Morphology-Dependent Interpolation Procedure (MDIP), belongs to the family of interpolation algorithms classified as contour-specific since they attempt to exploit the specific topologic and morphologic properties of contour lines (Yoeli, 1975; Clarke et al., 1982). However, MDIP algorithm exhibits a major improvement in comparison to the existing ones: each point is interpolated by means of the technique most suited to the morphologic characteristics of the neighboring area, namely: the method by which a skilful reader would determine the height of that point on a contour map.

The results obtained proved that the new method is 5-8 times more accurate than the commonly employed techniques; hence, the DTM data generated in this way faithfully reflect the most common topographical configurations found in nature (Carrara, 1986; Carla' et al., 1987a).

An example of perspective map obtained from a high-resolution DTM is shown in Fig. 7, where the morphology of the Upper Maroggia basin (Umbria, Central Italy) is displayed.

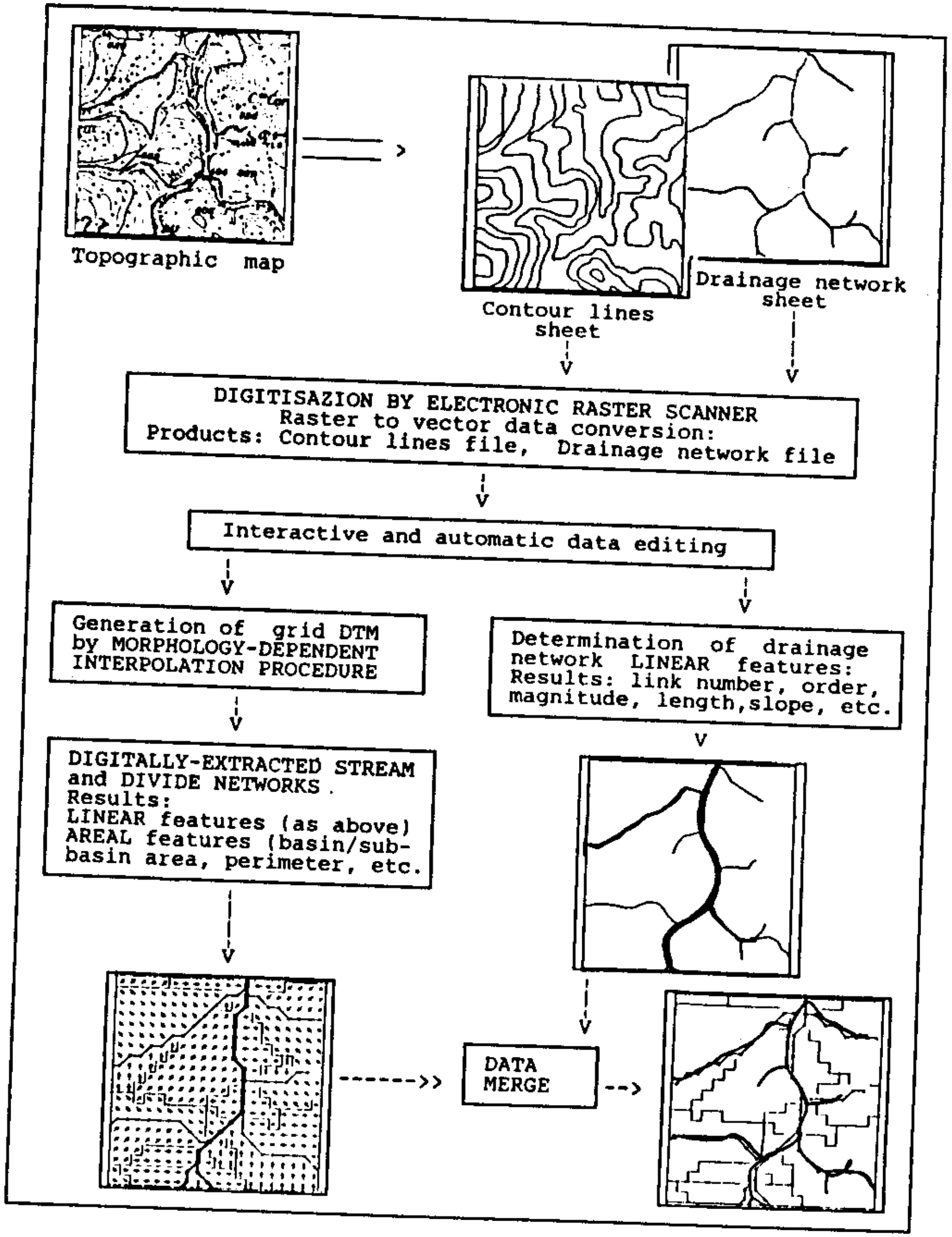

Fig. 6. Flow-chart showing the different phases of the investigation.

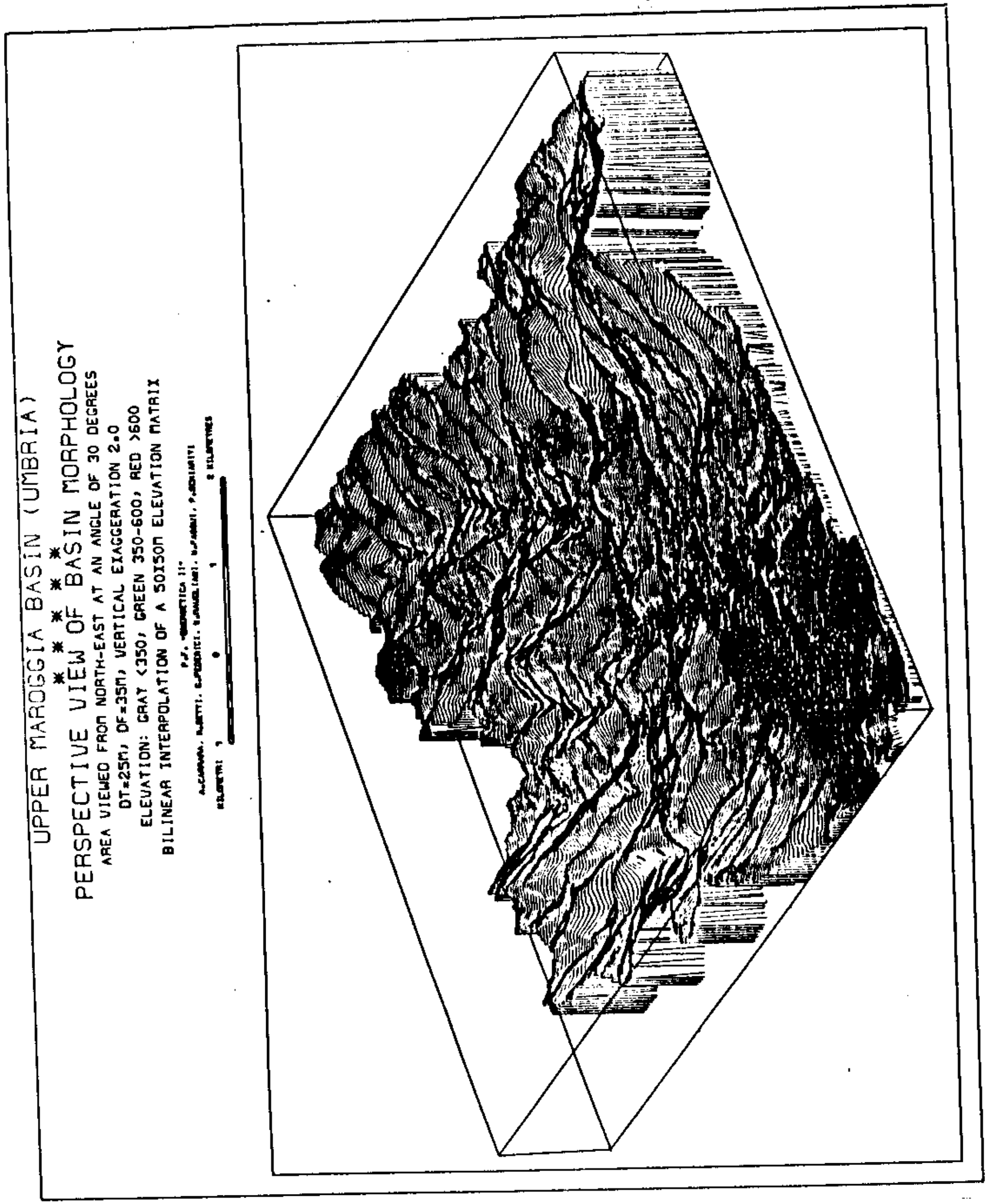

Fig. 7. Example of perspective map of basin morphology.

4.1.2. Drainage-divide networks derived from high-fidelity DTM

As previously stated, among the different possible applications of DTM, those related to hydrology and geomorphology play an important role. In particular, automatic identification of stream-lines and divides allows the construction of distributed hydrologic simulation models (Beven & Kirkby, 1979). Likewise, the partitioning of watersheds into subbasins and main slope-units greatly facilitates those investigations aimed at assessing regional slope-instability hazard by means of geostatistical models (Carrara, 1983, 1984).

A few investigators have long attempted to extract drainage networks and basin/subbasin morphologic parameters from digital terrain models (Puecker & Douglas, 1975); however, only recently has the problem received increased attention (O'Collaghan & Mark, 1984; Jenson, 1985: Band, 1986); this last work being of particular interest. Yet the complete achievement of this task seems to require further efforts and experimental tests.

Consequently, the first application of the DTM data produced by the new interpolation procedure consisted in an attempt to identify automatically basin drainage lines and divides, and to calculate basin/subbasin main geomorphologic parameters.

In order to accomplish this task, a set of procedures (named BACINI-1) was set up; while some of them are derived from literature, most constitute an original approach to the problem at hand.

The method is based on a simulation model of "overland flow concentration" generated by an hypothetical spatially homogeneous rainfall event, throughout a completely impermeable area. Under such simple circumstances, the problem, which in nature clearly depends on a very large set of complex factors, reduces to assessing the control exerted by ground morphology on flow lines.

In order to analyze flow lines and terrain morphology relationship, the area to be investigated is divided into square cells (grid-units or land-unit parcels). In the center of each grid-unit, elevation is determined by means of the previously described interpolation algorithm; hence the resulting elevation matrix (DTM) constitutes the input information of the whole procedure that includes the following phases:

-a) Data pre-processing: a quality test is performed to identify those DTM points ("pits") whose height is lower than that of their eight-connected neighbors. In nature such a circumstance occurs in some landscapes (karst areas, recently glaciated zones, etc.); however, "pits" most frequently reflect either failure of the interpolation algorithm used, or inadequacy of the grid-size selected. Whatever the cause of these closed depressions, they can significantly hamper any hydrological data processing; hence, they are resolved by a local two-step filtering procedure.

-b) Data processing: from DTM elevations two data matrices are derived: the first indicates the direction along which water from each grid cell would flow towards one of its of its eight-connected neighboring cells; the second provides for each cell the total number of cells that "spill" into it, that it, the upstream contributing area drained by each land-unit parcel. From these two simple (but computationally costly) data sets a fully connected, ordered drainage network and a complementary divide network are generated. Depending on the value of a set of parameters, the drainage-divide networks will be characterized by a different degree of generalization, in a similar manner as happens when drainage lines of an area are displayed on topographic sheets of different scales.

-c) Data post-processing: having acquired the above groups of data, it is readily possible to produce a large spectrum of morphologic parameters: some correspond to those routinely acquired by traditional methods (link length, number, order, etc.), others can be considered unique (subbasin area, aspect, mean slope, etc.) because their acquisition by manual techniques would require a tremendous amount of time and work. They are (for terminology cf. Jarvis, 1984):

-a) outlet number
-b) link number
-c) number of the two tributaries of the link
-d) coordinates of the link up/down-stream nodes (junctions)
-e) link value of topologic vector
-f) link order (Strahler)
-g) link magnitude
-h) number of cells constituting the link
-i) link length
-j) link mean slope
-k) link subbasin area
-l) total basin area drained by the downstream node of the link
-m) area of right/left sides of link subbasin (main slopes)
-n) perimeter of right/left sides of link subbasin
-o) mean aspect and slope of right/left sides of link subbasin.

The technique outlined has been successfully tested in a three waters from Central and Southern Italy, differing in terms of size, morphological setting and hydrological characteristics.

As an example of the results obtained, in Fig. 8 it is portrayed the drainage-divide networks which were derived automatically from the same DTM data shown in Fig. 7.

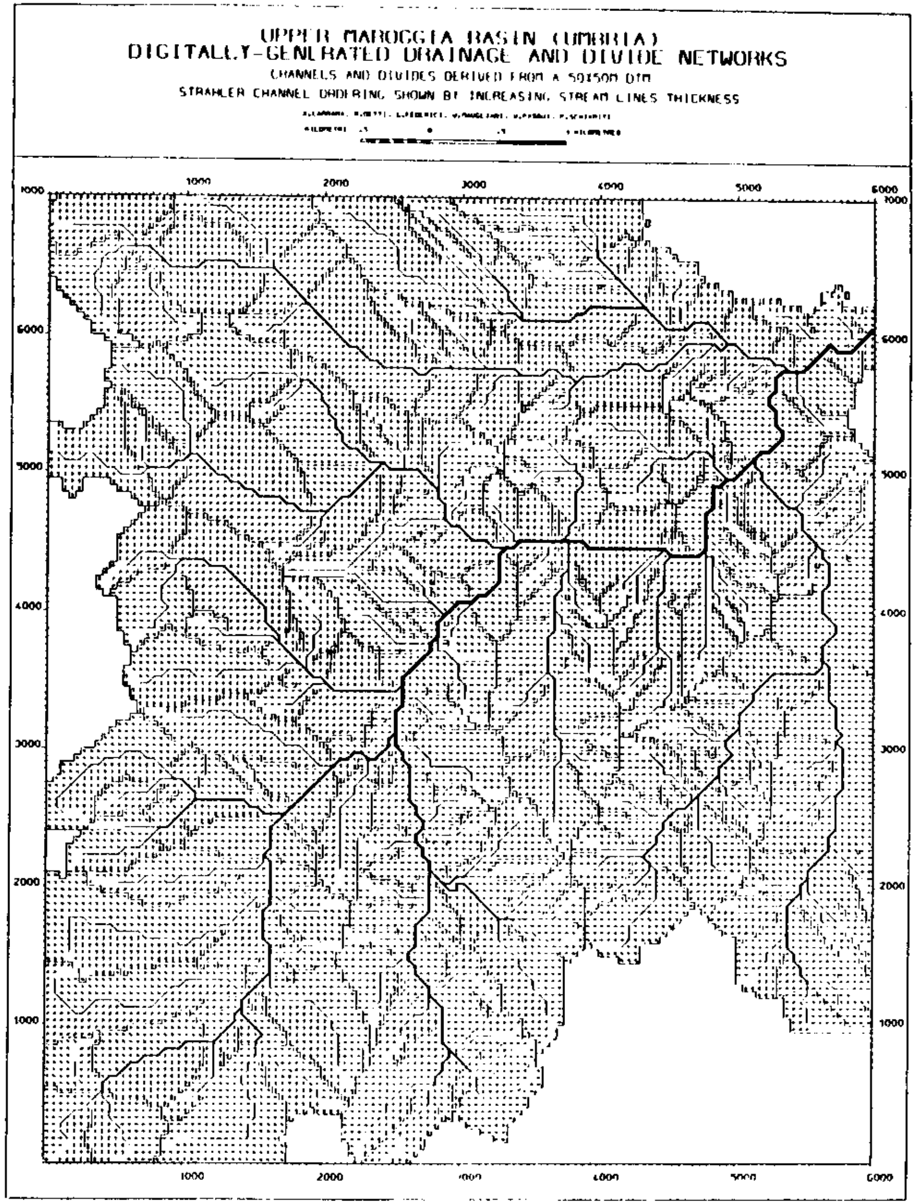

Fig. 8. Upper Maroggia basin (Central Italy). Digitally-generated drainage and divide networks derived from a high-fidelity DTM. Arrows indicate mean aspect of right and left sides (main slopes) of each subbasin.

5. CONCLUDING REMARKS

From the above short review on the development and application of geographical information systems to water and land resources assessment, the following concluding remarks can be put forth.

-a) The development and implementation of a modern GIS requires significant financial and technological resources. Hence, before starting a project involving its creation, a carefully-designed strategy must be set up. This should cover the following aspects.

- First the goals of the project must be clearly defined and the actual/potential users identified.
- Decision has to be taken on type, quality and quantity of data to be collected and on procedures for their acquisition, all of them being heavily dependent on the nature of the project. For reconnaissance surveys over wide, ill-known regions, aerial photography and satellite imagery can be the primary source of data gathering; whereas for detailed investigations on small zones, site-analysis is always needed.
- Where advanced computer technologies are not readily available, a feasible approach could consist in contracting out to reliable government or private agencies the work requiring sophisticated hardware devices (namely: digitization by electronic scanners and final drafting for printing). In this way available personnel and financial resources can be concentrated on data processing, analysis and "temporary" map display which are, on the other hand, the most relevant phases of the project.

-b) When access to adequate hardware facilities is possible, and software is clearly designed, developed and implemented, digitization constitutes the most time-consuming and costly phase of the whole process for producing digital terrain models, ground geomorphometric or other environmental maps whose data can be extracted from existing topographic bases. Indeed, digitization costs may represent a serious limitation to a broad application of these numerical techniques to land evaluation and planning. However, it should be pointed out that in the near future, the work involved in digitizing contour lines or drainage networks of topographic maps may become unnecessary, since cartographic automation will probably begin at the stage of survey. This trend is already being followed by some government mapping agencies of various countries (USA, Sweden, U.K., Italy, etc.). In addition, as previously mentioned, electronic scanners are becoming more and more efficient and can constitute a suitable tool for the digitization of existing topographic maps. Lastly, future space-borne sensors should provide detailed information on ground relief. In this case they might become the primary source of data to create digital terrain models.

-c) Data acquisition and digitization for other environmental features (geology, land use/cover, etc.) seem to remain a major problem even in the long-term. Hopefully, progresses in raster scanner technology and in pattern recognition algorithms will permit digitizing a wider spectrum of map types (color and multiple symbols and lines). In addition, the new satellite digital, optical/radar sensors (SPOT, Thematic Mapper, SAR) should provide imageries characterized by a degree of spatial resolution that can fulfill the requirements of land evaluation/planning projects.

-d) As far as geocoding structure (cellular vs polygonal) is concerned, the main issue does not seem to regard which is the most efficient but, depending on the scope of the investigation, nature of the data and type of analyses to be carried out, how to move quickly and efficiently from one to another.

-e) Lastly but most importantly, the quality of the data to be analyzed and displayed must constitute the main task of any project aimed at making a GIS operational. Indeed, too frequently sophisticated cartographic/geographic information systems have been developed, implemented and employed to process almost useless (but easy-to-gather) environmental data.

As a result, it is apparent that geographical data processing is an emerging discipline whose major changes and advancements will likely occur in the realm of thematic mapping, modeling and simulation of environmental characteristics. As computer hardware/software technology improves, a great number of new maps, varying greatly in nature, content and aesthetics, will be produced quickly and at low-cost. Most of them, portraying spatial, topological and functional relationships between environmental entities, will constitute a fundamental aid in carrying out land evaluation/water resources assessment projects.

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